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Acoustoelectric Effect In Solid State Materials and Devices

Awadhesh Prasad
Associate Professor in Physics, Jagjiwan College, Ara Bhojpur, Bihar–802301

Abstract: **Acoustoelectric effect is the appearance of a dc electric current, when an acoustic wave passes through a conducting medium. This paper reviews the study of Ultrasonic stress on the semiconductor materials and devices used in various scientific and other measurements. A historical review of earlier findings is also reported with special reference to associated mechanisms. Ultrasonic stress studies in solid state devices require further attention and the work done in this area is also discussed. Different kinds of the mechanism, interpretation responsible for the change in the characteristics of the solid state devices and materials have been discussed. Ultrasonic stress produces a pressure effect on a target object placed in the ultrasonic field. Ultrasonic wave may be regarded as a coherent beam of phonons, absorbed in front of the material. In terms of the charge carriers, an electron hole pair is created due to the Ultrasonic field.**

Keywords: **Intervalley Scattering, Free electrons of the materials, Resistance of the material, Ultrasonic stress, Radiation Pressure, Ultrasonic Amplifier, Bunching of electrons and Holes in a Material, Carrier Mobility.**

I. INTRODUCTION

When a sinusoidal Ultrasonic wave propagates through a semiconductor, it gives rise to an electric field travelling through the semiconductor material with the velocity of the Ultrasonic wave. A dc field, under the action of the travelling ac field is generated across the semiconductor material while the wave traverses the semiconductor material. Ultrasonic energy (signals) containing phonons shower down on unexcited atoms. The phonons are absorbed by the atoms of the said solid state materials and the devices. The energy of the phonon is converted into internal energy of the atom. The atom is then raised to an excited quantum state. Later on, the excited atom radiates this energy. In this way, there is a travelling wave amplification through semiconductor materials and solid state devices. Under the assumption of the conservation of momentum, Weinreich has derived a relationship between the absorption coefficient of ultrasonic waves and the ultrasonic field:[1 – 14]

$$\alpha_i = \delta_{ne} V_s E_{ae} / Q \quad \text{-------- (1)}$$

α is the attenuation per unit length due to conduction electrons in nepers – cm^{-1},
n the density of conduction electrons in cm^{-3},
V_s the ultrasonic wave velocity in cm – sec^{-1},
Q, the ultrasonic – power density in watt – cm^{2},
E_{ae}, the ultrasonic electric field in volt – cm^{-1},
δ, the numerical factor depending on the scattering process of conduction electrons. The field created in the solid state devices and materials due to the ultrasonic stress effect is defined as the electric field equivalent to the dc forces acting upon the electrons due to the ultrasonic wave. Weinreich pointed out, the rate of loss of momentum from the ultrasonic wave (which is equal to the rate of energy loss divided by the velocity of sound) is a dc force in the direction of propagation of sound and is equivalent to an electric field.

The concept of a deformation potential is useful in discussing the motion of electrons and holes in a semiconductor material and devices in the presence of ultrasonic deformation of the semiconductor material. In the simplest form, deformation potential is applicable to low energy electrons and holes whose bands have a simple structure, the assumption is that such a particle has a potential energy V_I proportional to the dilatation of the semiconductor material:

$$V_I = -\varepsilon_1 \Delta \quad \text{---------} \quad (2)$$

ε_1 is a constant and Δ the dilatation. This interaction leads to forces exerted on particles by ultrasonic wave and in certain cases to radiation of ultrasonic wave by particles.

Treating the ultrasonic stress effect on the semiconductor materials and devices classically, ultrasonic wave lengths are much larger than carrier mean free paths (and the periods much larger than mean free times), describing the net particle current j in the usual macroscopic way as being composed of a drift term and a diffusion term

$$j = D\left(\frac{F}{KT} - \nabla\right)\eta \quad \text{------ (3)}$$

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η is the particle density, F the force applied to the particles, KT the thermal energy, D the diffusion constant.

To avoid space charge difficulties, in addition to the deformation potential force - ∇V_I, the force exerted by electric fields resulting from the redistribution of charges is also considered. For small sinusoidal disturbances, induced electrostatic potential is proportional to the deformation potential of the applied ultrasonic wave. The change in the ultrasonic propagation properties of the medium can be thought of as the continual addition to the original wave of a wave which is radiated by the redistributed carriers. The ultrasonic stress effect on the semiconductor materials and devices produce simultaneous bunching of electrons and holes in a semiconductor under the action of the deformation potential of a travelling ultrasonic wave.

II. DISCUSSION

Propagation of an ultrasonic wave causes a change in the resistance due to the heating of the carrier caused by absorption of energy from the ultrasonic wave and the corresponding change in carrier mobility.

Ultrasonic wave propagation through a semiconductor material and solid state devices lead to thermal motion and lattice vibration analogous to the photons in the electromagnetic waves. The mode of ultrasonic wave propagation through a semiconductor and solid state material gives information about the lattice vibration. The acoustical branch of lattice spectrum is described by the dispersion relation.

$$W^2 = C\left(\frac{1}{M} + \frac{1}{m}\right) - C\left[\left(\frac{1}{M} + \frac{1}{m}\right)^2 - \frac{4\sin^2 ka}{Mm}\right]^{1/2} \qquad - (4)$$

C is elastic force constant.

m is the linear array of identical atoms with interatomic spacing a

K is the wave vector

W is the angular frequency

One dimensional crystal formed by the alternate placing of two different atoms of masses M and m.

m < M

The maximum possible angular frequency for the acoustic mode is $W_1 = (2c/M)^{1/2}$

which is independent of the mass of the lighter atom. The acoustic mode minimises changes in the second nearest neighbour distance by maximising changes in the nearest neighbour separation. The nearest neighbour stiffness constant is considerably larger than any other, each harmonic oscillator of the acoustic mode will store a considerable amount of energy.

The range of frequency for which K must be complex extends from $W_1 = (2c/M)^{1/2}$ to $W_2 = (2c/m)^{1/2}$

The width of the forbidden band is $(W_2 - W_1)$.

The mass ratio (m/M) determines width of the forbidden band.

Both electromagnetic and acoustic waves exert forces of radiation upon an obstacle placed in the path of the wave, the forces being proportional to the mean energy density of the wave motion.

The energy of a lattice vibration is quantized. The quantum of the energy is called a phonon. Elastic wave in crystals are made up of phonons. Thermal vibrations in crystals are thermally excited phonons.

The energy of an elastic mode of angular frequency W is $E = (n + \frac{1}{2})\hbar w$.

when the mode is excited to quantum number n and the mode is occupied by n phonons. The term $\frac{1}{2}\hbar w$ is the zero point energy of the mode.

A simple model of phonons in a crystal is defined as the vibrations of a linear lattice of particles connected by springs. Quantizing the particle motion for a harmonic oscillator. Transforming from particle coordinate to phonon coordinate known as wave coordinate as it represent a travelling wave.

Let N particles of mass M be connected by springs of force constant C and length a. For fixing the boundary conditions, the particle form a circular ring. Considering the transverse displacements of the particles out of the plane of the ring. The displacement of the particle s is q_s and its momentum is p_s. The Hamiltonian of the system is

$$H = \sum_{s=1}^{n} \left\{ \frac{1}{2M} p_s^2 + \frac{1}{2} C (q_{s+1} - q_s)^2 \right\} \quad (5)$$

The Hamiltonian of a Harmonic oscillator is

$$H = \frac{1}{2M} p^2 + \frac{1}{2} CX^2 \qquad ------ (6)$$

And the energy eigen values are, for n = 0, 1, 2, 3, …..

$$E_n = (n + \tfrac{1}{2})\hbar w. \quad ------ (7)$$

An ultrasonic wave exerts a static pressure on any interface or medium across which there is a decrease in ultrasonic intensity in the direction of wave propagation.

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This static pressure is distinct from the oscillating particle pressure of the wave. The force is proportional to the mean energy density of the wave motion. In case of complete absorption of a finite beam of plane waves,

$$F = W/C \qquad \text{-----------} \qquad (8)$$

F is the force due to radiation pressure.
W is the ultrasonic power.
C is the ultrasonic velocity in the medium.

The amount of energy carried by sound vibration in 1 sec through an area of $1cm^2$ perpendicular to the direction of propagation, determines the strength, or intensity, of the sound.

For a plane progressive Sine wave, the sound intensity I is expressed in Watt/ Cm^2 or erg/ sec – cm^2 as

$$I = P^2 / 2\rho C$$
$$= (½) V^2\rho C = PV/2 \text{ --- } (9)$$

P is the pressure of the ultrasonic wave at any point in the medium.
ρC is specific acoustic impedance of the medium,
ρ is the density of medium,
C is ultrasonic velocity in the medium,
V is the velocity of the vibrational movements of the particles of the medium through which an ultrasonic wave is propagated.

The acoustic pressure in water irradiated with ultrasonic waves of intensity I is given as

$$P = \sqrt{2\rho C I} \qquad \text{----------} \ (10)$$

The intensity I is proportional to the square of the displacement. If I_O is the initial intensity, in watts per square centimetre of a progressive ultrasonic wave, the intensity at a distance X is

$$I = I_O\, e^{-2\alpha X} \qquad \text{----------} \ (11)$$

where is the loss coefficient in nepers per cm of the wave through a medium.

The time averaged force per unit area on the surface on an obstacle termed as radiation pressure is related to the time averaged momentum flux of the ultrasonic wave.

The presence of an ultrasonic field, the carriers of the device acquire energy from the field and lose it to phonons, by emitting more phonons than those absorbed. The carriers on the average, acquire more energy than they have at thermal equilibrium. The average energy of the carriers also increases, and they acquire an effective temperature Te, which is higher than the lattice temperature T.

The presence of a sinusoidal travelling acoustic wave gives rise to a sinusoidal electric field, this field travelling through the material with the same velocity as that of the acoustic wave. For most of the conduction electrons, this component of velocity will be much larger in magnitude than the speed of acoustic wave, so that these electrons are out of phase with respect to the travelling electric field. Thus the time average of this field over their trajectories is zero, and these electrons are essentially unaffected by the presence of the acoustic wave. There are a few electrons, having components of velocity parallel to the wave which are comparable to the speed of the wave. These electrons are capable of being trapped by the moving electric field so that their time – averaged velocity in the direction of the field is exactly that of the field. Among these electrons, those having a maximum energy will be found to give rise to a net electric current.

In an n – type semiconductor, these electrons are in the conduction band, such a generation of en electric current by a travelling acoustic wave is defined as the acoustoelectric current. These are the consequences of the ultrasonic stress effect on the material.

The acoustoelectric effect has been explained by wave mechanics using one electron approximation and Schroedinger's equation. The acoustoelectric effect is the production of a dc electric field under the action of a travelling acoustic wave in a medium containing free carriers. The term acoustoelectric effect refers to the appearance of a dc electric field along the direction of propagation of a travelling acoustic wave in a medium containing mobile charges and known as wave particle drag.

Ultrasonic wave changes the resistance of the device which is due to the compression and tension by the ultrasonic wave (stress).

III. CONCLUDING REMARKS.

The present study would help the manufacturer's and users to add a proper necessary correction factor while using the solid state devices in the ultrasonic (stress) field.

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