

Acoustic Phonon Controlled Electron Mobility in Semiconductor

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ABSTRACT: The temperature dependence of electron drift mobility in semiconductor has been investigated using relaxation time approximation when the electrons are dominantly scattered by deformation potential and piezoelectric acoustic phonons. Calculations are carried out both for parabolic as well as non-parabolic conduction band structure taking into account elastic scattering mechanisms. The numerical computations are performed to observe the effect of non-parabolicity on the electron mobility in important covalent semiconductor like Si and III-V compound like GaAs at lattice temperatures from 1K to 200K.

KEYWORDS: Semiconductor, Scattering Rate, Acoustic Phonon, Mobility.

I. INTRODUCTION

The mobility of the free electrons is the most important parameter for characterizing the transport characteristics in semiconductor devices. A great deal of attention has been paid to this parameter and many efforts have also been focused on theoretical models of carrier mobility in semiconductors [1-4]. The success of these models largely depends on the proper formulation of different type of scattering mechanisms and one must know which type of scattering is predominant in a particular material under the prevalent condition of lattice temperature T_L and free carrier concentration n_0 . The free carriers are dominantly scattered by the optical and intervalley phonons above the lattice temperature of 100K and by the impurity ions at very lower lattice temperature range. In between these two extreme temperatures the free electrons interact strongly with intravalley acoustic phonons. The impurity scattering can be suppressed by dielectric engineering but the scattering by acoustic phonons is intrinsic to the semiconductor and cannot be eliminated. Thus the intrinsic mobility determined by acoustic phonon scattering alone provides an important upper limit for the achievable mobility of free electrons in a semiconductor. The free electrons in a covalent semiconductor interact dominantly only with acoustic phonons through deformation potential. On the other, if a semiconductor consists of dissimilar atoms such as GaAs, the bonds are partly ionic and the unit cell does not contain a centre of symmetry and electrons interact with acoustic phonons due to both deformation potential as well as piezoelectric coupling [3, 5-7].

The advanced Si technology has prompted most of the studies in semiconductor physics. Along with these studies a considerable number of works have also been initiated on III-V and II-VI compound semiconductors. Gallium Arsenide, one of the III-V-compound semiconductors has attracted considerable interest for application in semiconductor heterostructures and nanostructures because of its high electron mobility. It finds use in many devices like tunnel diodes, Gunn effect devices, lasers, etc. Thus a good number of theoretical studies on the conductivity characteristics have been reported starting from a rather low temperature to high temperatures both in bulk semiconductors as well as in two-dimensional electron gas formed in semiconductor surface layers [1-10,]. In these analyses, a detailed physical formulation of various scattering mechanisms like ionized impurity scattering, acoustic phonon scattering, piezoelectric scattering, polar and non-polar optical phonon scatterings, carrier-carrier scattering, and alloy scattering has been made to accurately determine the variation of mobility with carrier concentration and temperature.

GaAs is a direct semiconductor at which the minimum of the conduction band is situated in the centre of the Brillouin zone and near the Γ -point minimum the energy is isotropic but non-parabolic [11]. For values of wave vector far from the conduction band minima, the energy deviates from the simple quadratic expressions and non-parabolicity occurs. Ghorai et al [5-8] have reported few studies on electron transport in elemental as well as compound semiconductors giving due account to the effect of non-parabolicity of the conduction band under different prevalent conditions of

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scattering mechanisms. In those studies it has been observed that the non-parabolicity factor influences the transport parameters in a very complex manner. Thus it would be interesting to determine the lattice temperature dependent mobility expressions of the electrons for acoustic phonon scattering mechanisms in bulk semiconductor introducing the non-parabolicity factor in the calculation. In this paper, calculations of the electron mobility in n-type Si and GaAs semiconductor for non-degenerate electron ensemble is estimated both for parabolic and non-parabolic band structure considering deformation potential acoustic phonon and piezoelectric acoustic phonon scattering. Thus we may observe the effect of non-parabolicity on the lattice controlled electron mobility characteristics in semiconductors. The relaxation time approximation approach is used to investigate mobility characteristics of free electrons taking into account elastic scattering mechanism types.

II. THEORETICAL MODEL

The electron mobility can be determined by solving Boltzmann transport equation in the relaxation time approximation as [4]

$$\mu = \frac{e\langle\tau(\epsilon)\rangle}{m_{\mu}^*} \quad (1)$$

where $\langle\tau(\epsilon)\rangle$ is the average relaxation time over the electron energies ϵ , e is the electronic charge and m_{μ}^* is the mobility effective mass of the electron.

The acoustic phonon limited effective mobility (μ_{ac}) can be calculated taking the individual contribution of the mobility (μ_{dp}) by deformation potential phonon scattering and the mobility (μ_{pz}) by piezoelectric phonon scattering with the help of the well-known Mathiesen Rule as [4]

$$\frac{1}{\mu_{ac}} = \frac{1}{\mu_{dp}} + \frac{1}{\mu_{pz}}, \quad (2)$$

The non-parabolicity of the conduction band may be introduced through energy dispersion relation [12] of the form

$$\frac{\hbar^2 k^2}{2m^*} = \gamma(\epsilon) = \epsilon(1 + \alpha\epsilon). \quad (3)$$

Here k is the magnitude of the wave vector, \hbar is the Dirac constant and m^* is the effective mass of the electron at the bottom of the Γ -point. The non-parabolicity factor α can be given as

$$\alpha = \frac{1}{\epsilon_g} \left(1 - \frac{m^*}{m_0}\right)^2,$$

where ϵ_g being the direct energy gap at Γ -point, m_0 the mass of the free electron.

2.1 Acoustic Phonon Scattering

The scattering by acoustic phonons is intrinsic to the semiconductor and cannot be eliminated. The free electrons in covalent semiconductor like Si, Ge, etc. interact dominantly only with acoustic phonons through deformation potential. On the other, if semiconductors consist of dissimilar atoms such as GaAs, InSb, InAs, etc, the bonds are partly ionic and the unit cell does not contain a centre of symmetry and electrons interact with acoustic phonons due to both deformation potential as well as piezoelectric coupling [2-5]. The momentum relaxation times for acoustic phonon scattering have already been calculated according to traditional theory both for parabolic as well as non-parabolic band structure. Using those expressions the corresponding mobility expression will be formulated.

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2.1.1 Deformation Potential Scattering

The acoustic mode lattice vibration induced changes in lattice spacing, which change the band gap from point to point. Since the crystal is "deformed" at these points, the potential associated is called the deformation potential. Using the corresponding relaxation time for parabolic band structure, the mobility associated with the deformation potential scattering can be written as [4, 5]

$$\mu_{dp}^p(T_L) = \mathcal{A}_1 T_L^{-3/2}, \quad (6)$$

where $\mathcal{A}_1 = \frac{2\sqrt{2}\pi e \hbar^4 \rho v_s^2}{3\epsilon_a^2 m^{*5/2} k_B^{3/2}}$, ϵ_a is the deformation potential constant, ρ the crystal mass density, v_s being the average sound velocity through the crystal and k_B is the Boltzmann constant.

Again using the expression of relaxation time for non-parabolic band [5, 11] the mobility of electrons for the deformation potential scattering can be obtained as

$$\mu_{dp}^{np}(T_L) = \mathcal{A}_2 \phi_{dp}(\xi), \quad (7)$$

where

$$\mathcal{A}_2 = \frac{5\sqrt{2}\pi e \hbar^4 \rho v_s^2 \alpha^{3/2}}{8\epsilon_a^2 m^{*5/2}}, \quad \xi = \alpha k_B T_L,$$

$$\phi_{dp}(\xi) = G_{dp}(\xi) - H_{dp}(\xi) \left[1 - \sum_{n=1}^{\infty} \left\{ (-1)^{n+1} \prod_{i=1}^n \left(i + \frac{11}{2} \right) \right\} \xi^n \right],$$

$$G_{dp}(\xi) = \frac{1}{\xi^{3/2}} (1 + 3.95 \xi + 49.50 \xi^2 - 84 \xi^3 - 47.95 \xi^4),$$

$$H_{dp}(\xi) = \frac{99}{20 \xi^{1/2}} (1 + 17.50 \xi + 35 \xi^2 - 105 \xi^3 - 52.50 \xi^4).$$

2.1.2 Piezoelectric Scattering

In compound semiconductors like GaAs, there is no inversion symmetry and hence the electron may be scattered by the acoustic phonons due to piezoelectric coupling. The electron mobility due to this effect can be written for parabolic band as [4, 5]

$$\mu_{pz}^p(T_L) = B_1 T_L^{-1/2}, \quad (8)$$

where $B_1 = \frac{16\sqrt{2}\pi \hbar^2 \epsilon_d}{3ek_m^2 m^{*3/2} k_B^{1/2}}$, k_m being the piezoelectric coupling constant and ϵ_d is the static dielectric constant.

When the expression of relaxation time [5] for non-parabolic band is considered then the mobility of electrons associated with the piezoelectric scattering can be written as

$$\mu_{pz}^{np}(T_L) = B_2 \phi_{pz}(\xi), \quad (9)$$

where

$$B_2 = \frac{5\sqrt{2}\pi \hbar^2 \epsilon_d \alpha^{1/2}}{ek_m^2 m^{*3/2}},$$

$$\phi_{pz}(\xi) = G_{pz}(\xi) - H_{pz}(\xi) \left[1 - \sum_{n=1}^{\infty} \left\{ (-1)^{n+1} \prod_{i=1}^n \left(i + \frac{11}{2} \right) \right\} \xi^n \right],$$

$$G_{pz}(\xi) = \frac{1}{\xi^{1/2}} (1 + 10.16 \xi + 57.73 \xi^2 - 18.19 \xi^3 + 27.56 \xi^4 - 17.72 \xi^5),$$

$$H_{pz}(\xi) = \frac{693}{80 \xi^{-1/2}} (1 + 15 \xi + 33.75 \xi^2 - 7.50 \xi^3 + 15 \xi^4 - 11.25 \xi^5).$$

III. RESULT AND DISCUSSION

For the application of the above formulation we consider the most important covalent semiconductor like Silicon and another important III-V direct band gap compound with a zincblend crystal structure like Gallium Arsenide. It is obvious that the acoustic phonon controlled electron mobility in Si is associated only with the deformation potential phonon scattering but in GaAs the same mobility is controlled by both deformation potential and piezoelectric phonons. To observe the effect of non-parabolicity on the electron mobility in n-Si and n-GaAs in a temperature range from 1K up to 200K we use the material parameters of Si and GaAs listed in Table-1.

Table-1: Material Parameters of Si and GaAs [1, 2]

| Physical constants | Si | GaAs |
|--|-------|-------|
| Deformation potential, ϵ_a (eV) | 9.0 | 12.0 |
| Effective mass ratio (m^*/m_0) | 0.32 | 0.067 |
| Acoustic velocity, v_s (10^5 cm s^{-1}) | 9.037 | 5.2 |
| Density, ρ (g cm^{-3}) | 2.329 | 5.31 |
| Non-parabolicity factor, α (eV^{-1}) | 0.5 | 0.64 |
| Piezoelectric coupling constant, k_m | --- | 0.052 |
| Static dielectric constant, ϵ_d | --- | 13.5 |

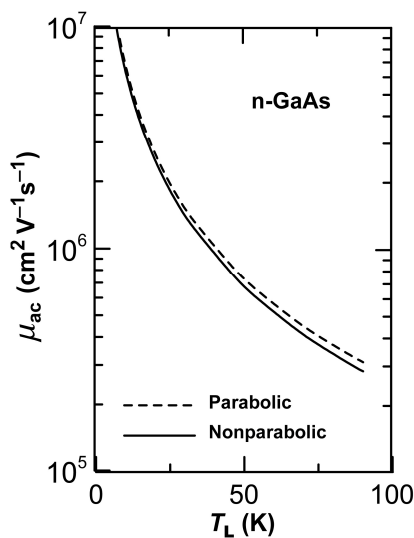


Fig.1 Dependence of acoustic phonon controlled electron mobility upon lattice temperature in n-type GaAs.

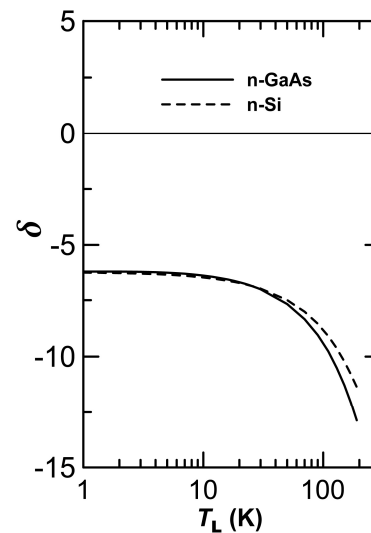


Fig.2 Dependence of percentage deviation of mobility due to non-parabolicity upon lattice temperature.

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From the Eqns.(6) to (9), it is noticeable that the mobility values depend on lattice temperature T_L in a very complex manner when non-parabolicity of the conduction band is taken into account in comparison to what follows for the parabolic band structure. In Fig.1 the dependence of phonon controlled electron mobility upon lattice temperature is plotted for both parabolic and non-parabolic band. From the figure it is observed that the temperature dependent electron mobility decreases rapidly with the rise of lattice temperature both for parabolic and non-parabolic band. In both cases the qualitative dependence is almost the same. It is also seen that due to non-parabolicity of the conduction band the lattice controlled electron mobility is slightly less in comparison to what follows for the parabolic band. It is also seen that with the rise of lattice temperature the mobility values decreases more and more and hence the effect of non-parabolic band becomes more prominent. It is because the carriers become more energetic due to high lattice temperature and then the non-parabolicity comes into effect. To estimate the effect of non-parabolic band on the drift mobility of the electrons we may calculate the percentage deviation as

$$\delta = \frac{\mu_{ac}^{np} - \mu_{ac}^p}{\mu_{ac}^p} \times 100\%. \quad (10)$$

Fig.2 shows how the percentage deviation of the drift mobility due to non-parabolicity of the conduction band in Si and GaAs depends upon the lattice temperature. Since δ is always negative, finite non-parabolicity affects as lower value of temperature dependent electron mobility in comparison to that corresponding to a parabolic band. The magnitude of δ assumes a finite value at low lattice temperature. Initially it increases slowly with the rise of lattice temperatures and later on it increases at a much faster rate when the lattice temperature becomes relatively higher.

IV. CONCLUSION

In the present investigation we have calculated phonon limited electron mobility using a simple model of non-parabolic conduction band. In the study we observe that the finite non-parabolicity affects the mobility values particularly when the free carriers are energetic. Thus we may conclude that in the study of electron transport in semiconductors under high-field condition or at higher temperatures, the effect of non-parabolicity has to be included.

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