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ORIGINAL ARTICLE

Electron Mobility in InP at Low Electric Field Application

M. Mahmoodi and A. Feyzi
Physics Department, Payame Nour University of Fariman, Fariman, Ira

ABSTRACT
Temperature and doping dependencies of electron mobility in InP semiconductor has been calculated using an iterative technique. The following scattering mechanisms, i.e, impurity, polar optical phonon, acoustic phonon and piezoelectric are included in the calculation. It is found that the electron mobility decreases monotonically as the temperature increases from 100 K to 600 K. The low temperature value of electron mobility increases significantly with increasing doping concentration. The iterative results are in fair agreement with other recent calculations obtained using the relaxation-time approximation and experimental methods.
Keywords-: *Polar optical; ionized impurity scattering; electron mobility*

INTRODUCTION

InP is a direct band gap semiconductor, and therefore has a high breakdown field and low thermal generation rate. These properties combined with good thermal conductivity and stability make InP an attractive material for high power, high temperature and radiation harsh environment electronic devices. Monte Carlo simulations predict a peak electron velocity of 1×10^5 ms^{-1} and a saturation electron velocity of 0.7×10^{-5} ms^{-1} [1-5]. This makes possible high frequency operation of InP devices. For the above stated reasons, InP is of great interest for power FETs and optoelectronic device structures. InP based field-effect transistors have been reported to exhibit continuous wave outputs up to 4.9 W/mm [6] and high frequency operation [6] at f_T = 55 GHz and f_{max}=110 GHz.
The low-field electron mobility is one of the most important parameters that determine the performance of a field-effect transistor. The purpose of the present paper is to calculate electron mobility for various temperatures and ionized-impurity concentrations. The formulation itself applies only to the central Γvalley conduction band. We have also consider band non-parabolicity, admixture of p-type valence-band wave functions, degeneracy of the electron distribution to any arbitrary degree, and the screening effects of free carriers on the scattering probabilities. All the relevant scattering mechanisms, including the two-mode nature of the polar optic phonon scattering, are taken into account. The Boltzmann equation is solved iteratively for our purpose, jointly incorporating the effects of all the scattering mechanisms. Our calculated results are compared with the available experimental data on both temperature and the free electron concentration dependence of mobility.

MODEL DETAILS

To calculate mobility, we have to solve the Boltzmann equation to get the modified probability distribution function under the action of a steady electric field. Here we have adopted the iterative technique for solving the Boltzmann transport equation. Under the action of a steady field, the Boltzmann equation for the distribution function can be written as,

$$\frac{\partial f}{\partial t} + v.\nabla_r f + \frac{eF}{\hbar}.\nabla_k f = \left(\frac{\partial f}{\partial t}\right)_{coll} \qquad (1)$$

Where $(\partial f / \partial t)_{coll}$ represents the change of distribution function due to the electron scattering. In the steady-state and under application of a uniform electric field the Boltzmann equation can be written as,

$$\frac{eF}{\hbar}.\nabla_k f = \left(\frac{\partial f}{\partial t}\right)_{coll} \qquad (2)$$

Consider electrons in an isotropic, non-parabolic conduction band whose equilibrium Fermi distribution function is $f_0(k)$ in the absence of electric field. Note the equilibrium distribution $f_0(k)$ is isotropic in k space but is perturbed when an electric field is applied. If the electric field is small, we can treat the change from the equilibrium distribution function as a perturbation which is first order in the electric field. The distribution in the presence of a sufficiently small field can be written quite generally as,

$$f(k) = f_0(k) + f_1(k)\cos\theta \qquad (3)$$

Where θ is the angle between k and F and $f_1(k)$ is an isotropic function of k, which is proportional to the magnitude of the electric field. $f(k)$ satisfies the Boltzmann equation 2 and it follows that,

$$\frac{eF}{\hbar}\frac{\partial f_0}{\partial t} = \sum_i \left\{ \int \cos\varphi f_1' \left[S_i'(1-f_0) + S_i f_0 \right] d^3k - f_1 \int \left[S_i(1-f_0') + S_i' f_0' \right] d^3k' \right\} \qquad (4)$$

In general there will be both elastic and inelastic scattering processes. For example impurity scattering is elastic and acoustic and piezoelectric scattering are elastic to a good approximation at room temperature. However, polar and non-polar optical phonon scattering are inelastic. Labeling the elastic and inelastic scattering rates with subscripts *el* and *inel* respectively and recognizing that, for any process i, $s_{eli}(k', k) = s_{eli}(k, k')$ equation 4 can be written as,

$$f_1(k) = \frac{\frac{-eF}{\hbar}\frac{\partial f_0}{\partial k} + \sum\int f_1' \cos\phi\, [S_{inel}'(1-f_0) + S_{inel} f_0]\, d^3k'}{\sum\int (1-\cos\phi) S_{el}\, d^3k' + \sum\int [S_{inel}(1-f_0) + S_{inel}' f_0']\, d^3k'} \qquad (5)$$

Note the first term in the denominator is simply the momentum relaxation rate for elastic scattering. Equation 5 may be solved iteratively by the relation,

$$f_{1n}(k) = \frac{\frac{-eF}{\hbar}\frac{\partial f_0}{\partial k} + \sum\int f_1' \cos\phi\, [n-1][S_{inel}'(1-f_0) + S_{inel} f_0]\, d^3k'}{\sum\int (1-\cos\phi) S_{el}\, d^3k' + \sum\int [S_{inel}(1-f_0) + S_{inel}' f_0']\, d^3k'} \qquad (6)$$

where $f_{1n}(k)$ is the perturbation to the distribution function after the n-th iteration. It is interesting to note that if the initial distribution is chosen to be the equilibrium distribution, for which $f_1(k)$ is equal to zero, we get the relaxation time approximation result after the first iteration. We have found that convergence can normally be achieved after only a few iterations for small electric fields. Once $f_1(k)$ has been evaluated to the required accuracy, it is possible to calculate quantities such as the drift mobility ⍰⍰, which is given in terms of spherical coordinates by,

$$\mu = \frac{\hbar}{3m^* F} \frac{\int_0^\infty (k^3/1 + 2\alpha F) f_1 d^3k}{\int_0^\infty k^2 f_0 d^3k} \qquad (7)$$

Here, we have calculated low field drift mobility in GAN and InN structures using the iterative technique. In the following sections electron-phonon and electron-impurity scattering mechanisms will be discussed.

Deformation potential scattering

The acoustic modes modulate the inter atomic spacing. Consequently, the position of the conduction and valence band edges and the energy band gap will vary with position because of the sensitivity of the band structure to the lattice spacing. The energy change of a band edge due to this mechanism is defined by a deformation potential and the resultant scattering of carriers is called deformation

potential scattering. The energy range involved in the case of scattering by acoustic phonons is from zero to $2vk\hbar$, where v is the velocity of sound, since momentum conservation restricts the change of phonon wave vector to between zero and $2k$, where k is the electron wave vector. Typically, the average value of k is of the order of 10^7 cm^{-1} and the velocity of sound in the medium is of order 10^5 cms^{-1}. Hence, $2vk\hbar \sim 1$ meV, which is small compared to the thermal energy at room temperature. Therefore, the deformation potential scattering by acoustic modes can be considered as an elastic process except at very low temperature. The deformation potential scattering rate with either phonon emission or absorption for an electron of energy E in a non-parabolic band is given by Fermi's golden rule as [2-5],

$$R_{de} = \frac{\sqrt{2}D^2_{ac}(m_t^{*2}m_l^{*})^{1/2}K_BT}{\pi\rho v^2\hbar^4}\frac{\sqrt{E(1+\alpha E)}}{E(1+2\alpha E)} \left[(1+\alpha E)^2 + 1/3(\alpha E)^2\right] \quad (8)$$

Where D_{ac} is the acoustic deformation potential, ρ is the material density and α is the non-parabolicity coefficient. The formula clearly shows that the acoustic scattering increases with temperature.

Piezoelectric scattering

The second type of electron scattering by acoustic modes occurs when the displacements of the atoms create an electric field through the piezoelectric effect. The piezoelectric scattering rate for an electron of energy E in an isotropic, parabolic band has been discussed by Ridley [4].

The expression for the scattering rate of an electron in a non-parabolic band structure retaining only the important terms can be written as [2-6]:

$$R_{PZ}(k) = \frac{e^2K_BTK_{av}^{\ 2}\sqrt{m^*}}{2\sqrt{2}\pi\hbar^2\varepsilon_s}\gamma^{-1/2}(1+2\alpha\varepsilon) \left[(1+\alpha\varepsilon)^2 + \frac{1}{3}(\alpha\varepsilon)^2\right] \quad (9)$$

Where ε_s is the relative dielectric constant of the material and K_{av} is the dimensionless so called average electromechanical coupling constant.

Polar optical phonon scattering

The dipolar electric field arising from the opposite displacement of the negatively and positively charged atoms provides a coupling between the electrons and the lattice which results in electron scattering. This type of scattering is called polar optical phonon scattering and at room temperature is generally the most important scattering mechanism for electrons in III-V semiconductors, and this is also the case in GaN and InN despite the fact that the optical phonon energy is particularly high at ~ 93 meV which suppresses the phonon population and also electrons must reach that energy before phonon emission is possible. The scattering rate due to this process for an electron of energy E in an isotropic, non-parabolic band is [2-6],

$$R_{PO}(\vec{k}) = \frac{e^2\sqrt{2m^*}\,\omega_{PO}}{8\pi\varepsilon_\circ\hbar}\left(\frac{1}{\varepsilon_\infty}-\frac{1}{\varepsilon_\circ}\right)\frac{(1+2\alpha E)}{\sqrt{\gamma(E)}} F_{PO}(E,E')\{N_{op},N_{op}+1\} \quad (11)$$

Where $E = E' \pm \hbar w_{po}$ is the final state energy phonon absorption (upper case) and emission (lower case) and Nop is the phonon occupation number and the upper and lower cases refer to absorption and emission, respectively. For small electric fields, the phonon population will be very close to equilibrium so that the average number of phonons is given by the Bose- Einstein distribution.

Impurity scattering

This scattering process arises as a result of the presence of impurities in a semiconductor. The substitution of an impurity atom on a lattice site will perturb the periodic crystal potential and result in scattering of an electron. Since the mass of the impurity greatly exceeds that of an electron and the impurity is bonded to neighboring atoms, this scattering is very close to being elastic. Ionized impurity scattering is dominant at low temperatures because, as the thermal velocity of the electrons decreases, the effect of long-range Coulombic interactions on their motion is increased. The electron scattering by ionized impurity centres has been discussed by Brooks Herring [5] who included the modification of the Coulomb potential due to free carrier screening. The screened Coulomb potential is written as,

$$V(r) = \frac{e^2}{4\pi\varepsilon_0\varepsilon_s}\frac{\exp(-q_0 r)}{r} \qquad (12)$$

Where ε_s is the relative dielectric constant of the material and q_0 is the inverse screening length, which under non-degenerate conditions is given by

$$q_0^{\,2} = \frac{ne^2}{\varepsilon_0\varepsilon_s K_B T} \qquad (13)$$

Where *n* is the electron density. The scattering rate for an isotropic, non-parabolic band structure is given by [2-6],

$$R_{im} = \frac{N_i e^4 (1+2\alpha E)}{32\sqrt{2m^*}\pi\varepsilon_s^{\,2}(\gamma(E))^{3/2}}\left[Ln(1+b) - \frac{b}{1+b}\right] \qquad (14)$$

$$b = \frac{8m^*\gamma(E)}{\hbar^2 q_0^2} \qquad (15)$$

where N_i is the impurity concentration.

RESULTS

We have just taken into account the temperature and electron concentration dependence of the electron mobility in the Γ valley, which arises due to the different scattering mechanisms. The effect of temperature on the electron mobility is shown in figure 1.

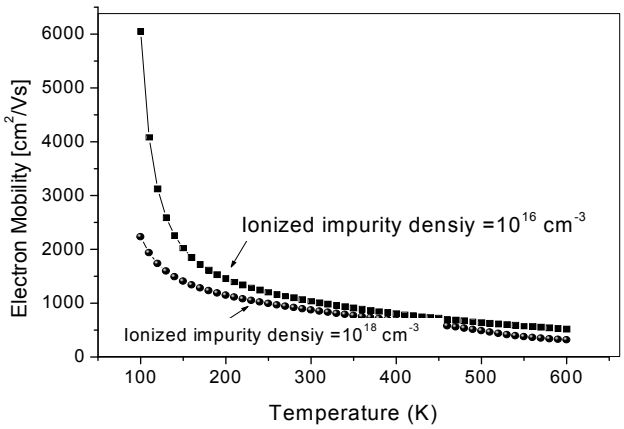

Fig. 1. Changes the electron mobility in terms of temperature in bulk InP at the different electron concentration

Figure 1 shows that sample with less electron density at all temperatures has more mobility and with increasing the temperature the mobility decrease in the definite temperature. The sample with more electron density has less mobility because in this sample the number of ionized impurity

centers is more and electron for more times will be affected by coulomb potential. The ionized impurity scatter rate is higher in this sample.

Figure 2 shows comparison the electron mobility of InP and AlP at different electron concentration.

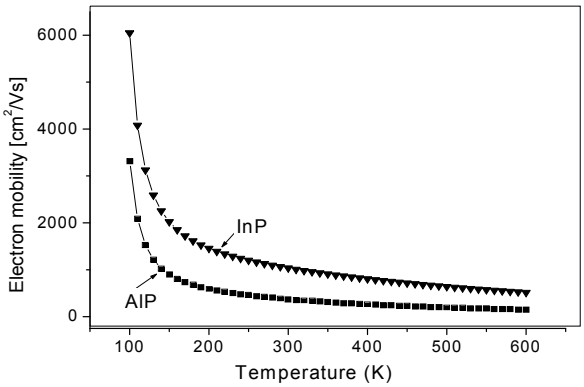

Fig. 2. Changes the electron mobility in terms of Temperature in bulk InP and AlP at the electron concentration 10^{16} cm^{-3}.

Our calculation results show that the electron mobility at the definite temperature 300 K for the InP semiconductor is gained about 1150 $cm^2v^{-1}s^{-1}$ and for AlP about 400 $cm^2v^{-1}s^{-1}$, also that the electron mobility InP is more than AlP. This is due to a small electron effect mass.

Figures 3 shows the electron mobility depends on the electron concentration at the different temperature in bulk InP material.

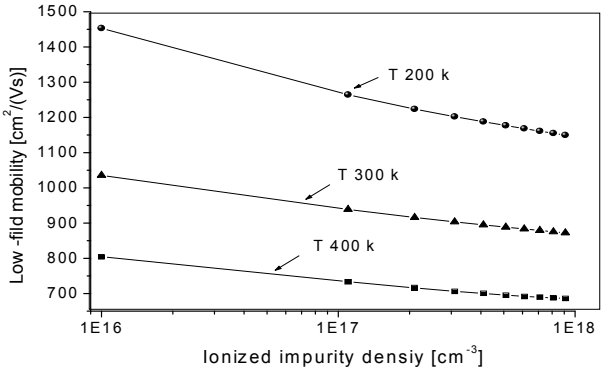

Fig. 3. Changes the electron mobility in terms of electron concentration in bulk InP at the different temperature.

Figure 4 shows comparison the electron mobility of InP and AlP at the different temperature .Our calculation results show that the electron mobility InP is more than AlP.

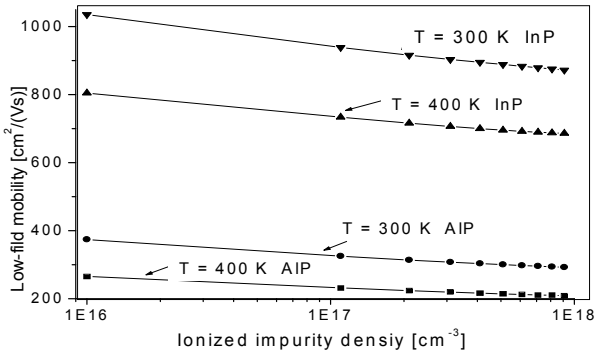

Fig. 4. Changes the electron mobility in terms of electron concentration in bulk InP and AlP at the different temperature.

Figure 4 show that The electron mobility decrease by the electrons concentrations increasing because electrons increasing causes increase of ionized impurity centers in crystals that it causes times more electrons under the influence of the Coulomb potential of impurity centers located that its result is increase of electrons scattering rate and finally decrease of electrons mobility.

CONCLUSION

Using an iterative method, it was shown that the electron scattering in the Γ valley substantially affects the electron mobility and transport properties in InP. It is shown that the electron mobility increase and Ohmic mobility drops by the same percent. This is caused by combined effects of effective heating of electron gas by electron scattering and predominantly forward peaked momentum relaxation for all electron momenta. InP semiconductor having high mobility of AlN because the effective mass is small compared with AlN.

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