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Correlation between Electron Mobility and Static Dielectric Permittivity of n-InSb

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Abstract: Direct analytical calculations of the static dielectric permittivity-dependent electron mobility due to different elastic scattering mechanisms for n-type InSb were carried out. The calculated static dielectric permittivity increases by increasing of donor concentration. The temperature dependence of the electron mobility from 10 K up to 300 K has been demonstrated. Generally, the electron mobility shows peak behavior in this range of temperatures. The direct correlation between the electron mobility and the static dielectric permittivity at 300 K was investigated. The dependence of the electron mobility on donor concentration was discussed both when the static dielectric permittivity is assumed to be varying and when it is assumed to be a constant. The difference in behavior was noticed particularly at high donor concentrations.

Keywords: static dielectric permittivity, electron mobility, scattering mechanisms

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1 Introduction

The carrier mobility is an important device parameter in semiconductor applications which has received considerable attention [1–3]. The evaluation of the electron mobility in an n-type semiconductor depends on a set of parameters such as temperature and doping concentration along with some material characteristics like static dielectric permittivity, electron effective mass, deformation potential and piezoelectric constant. As a result, because the electron mobility is a dielectric permittivity dependent, it is expected to be affected when the dielectric permittivity changes by considerable factors [4].

Material characterization studies in the past often assume that the dielectric permittivity is constant [5]. But in fact, as the impurity concentration changes, the static dielectric permittivity will be altered accordingly, and hence the electron mobility is varied.

The impurity concentration dependence of the static dielectric permittivity has been pointed out by Castellan and Seitz [6] taking into account the contribution of the impurity atoms to the polarization. Dhar and Marshak [7] have extended the Castellan and Seitz equation by considering the polarization of the host atoms and its effect on the polarization of the impurity atoms.

In this work, the electron mobility of n-type InSb is calculated considering the change of the static dielectric permittivity. Many types of elastic scattering mechanisms have been assumed. Scattering by deformation potential mode of lattice vibrations, piezoelectric lattice vibrations, ionized impurities and neutral impurities have been considered.

2 Theoretical model

Castellan and Seitz have pointed out the impurity concentration dependent static dielectric permittivity of the form [6]:

$$\varepsilon_s = \varepsilon_{const} + \frac{N_d \alpha}{1 - \frac{N_d \alpha}{3\varepsilon_{const}}} \tag{1}$$

where α is the polarizability of the impurity atom, ε_{const} is the dielectric permittivity of the pure host semiconductor and N_d is the concentration of impurity atoms.

Dhar and Marshak [7]have extended equation (1) to

$$\varepsilon_s = \varepsilon_{const} + \frac{N_d \alpha(\varepsilon_{const} + 2)(4\varepsilon_{const} - 1)}{9\varepsilon_{const} - N_d \alpha(\varepsilon_{const} + 2)} \tag{2}$$

where α is given by

$$\alpha = \frac{A}{1 - BN_d^{1/3}} \tag{3}$$

and A and B are constants.

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The electron mobility in semiconductors depends on the scattering processes. The main sources of scattering are lattice scattering and impurity scattering. Lattice scattering includes deformation potential and piezoelectric scattering while impurity scattering includes ionized impurity and neutral impurity scattering.

The deformation potential-limited electron mobility is given by [8]:

$$\mu_{dp} = \frac{2\sqrt{2\pi}C_{11}e(\frac{h}{2\pi})^4}{3E_1^2(m^*)^{5/2}(kT)^{3/2}} \tag{4}$$

where e is the electronic charge, k is Boltzmann constant, T is the temperature, m^* is the effective mass of the electron, h is the Planck's constant, C_{11} is the average longitudinal elastic constant of the semiconductor and E_1 is the acoustic deformation potential.

The piezoelectric potential-limited mobility is given by [8]:

$$\mu_{pz} = \frac{16\sqrt{2\pi}C_{11}(\frac{h}{2\pi})^2\varepsilon_o^2\varepsilon_s^2}{3eh_{pz}^2(m^*)^{3/2}(kT)^{1/2}} \tag{5}$$

where ε_o is the permittivity of free space and h_{pz} is the piezoelectric constant.

The ionized impurities-limited mobility is given by Brooks-Herring formula as [9]:

$$\mu_{=}\delta T^{3/2}\left\{\ln(1+\gamma) - \frac{\gamma}{1+\gamma}\right\} \tag{6}$$

$$\delta = \frac{128\sqrt{2\pi}\varepsilon_o^2\varepsilon_s^2(kT)^{3/2}}{N_i e^3\sqrt{m^*}} \tag{7}$$

$$\gamma = \frac{96\pi^2\varepsilon_o\varepsilon_s m^*(kT)^{3/2}}{h^2e^2N_i} \tag{8}$$

where N_i is the concentration of the ionized impurities which can be calculated from the relations [10]:

$$N_i = \frac{N_d}{1 + 2\exp\left[\frac{E_f - E_d}{kT}\right]} \tag{9}$$

$$E_f = E_c - kT\ln\left(\frac{N_c}{N_d}\right) \tag{10}$$

$$E_d = E_c - E_i \tag{11}$$

$$N_c = 2\left(\frac{2\pi m^* kT}{h^2}\right)^{3/2} \tag{12}$$

$$E_i = E_H\left(\frac{m^*}{m_o}\right)\left(\frac{1}{\varepsilon_s}\right)^2 \tag{13}$$

where E_f is the Fermi level, E_c is the bottom of the conduction band, N_c is the density of conduction band states, E_i is the ionization energy of the donors, m_o is the rest mass of the electron and E_H is the ionization energy of hydrogen atom (13.6 eV).

The neutral impurities-limited mobility is given by [8]:

$$\mu_n = \frac{e^3m^*\pi^2}{10N_n\varepsilon_o\varepsilon_s h^3} \tag{14}$$

where N_n is the concentration of the neutral impurities.

The total mobility (electron drift mobility) can be calculated using Mathiessen's rule [10]:

$$\frac{1}{\mu} = \frac{1}{\mu_{dp}} + \frac{1}{\mu_{pz}} + \frac{1}{\mu_i} + \frac{1}{\mu_n} \tag{15}$$

3 Results and discussions

Calculations of the electron mobility and the static dielectric permittivity were carried out for n-type InSb using direct numerical method. Our model assumes that no acceptors are present in the system, i.e. $N_a = 0$.

Table 1: Material parameters of InSb.

parameter	value
dielectric constant, ε_{const}	17.9
A	$2 \times 10^{-17}\ cm^3$
B	$5 \times 10^{-7}\ cm$
Electron effective mass, m^*	$0.014\ m_o$
Width of the forbidden gap, E_g	0.24 eV
Longitudinal elastic constant, C_{11}	6.67×10^{11} dyne/cm^2
Acoustic deformation potential, E_1	18 eV
Piezoelectric constant, h_{pz}	0.07 C/m^2

The donor concentration dependent dielectric permittivity of n-type InSb was calculated using equations 2 and 3. The parameters used in the calculations are listed in Table 1. Fig. 1 shows the variation of the static dielectric permittivity of InSb with donor concentration. It was noticed that ε_s increases as the donor density increases. At low impurity densities the static dielectric permittivity remains at the value of pure InSb (17.9). As the number of donors increases, the polarization due to presence of the impurities may cause the static dielectric permittivity to increase until a value at which polarization catastrophe may happen and hence the static dielectric permittivity tends to infinity [11].

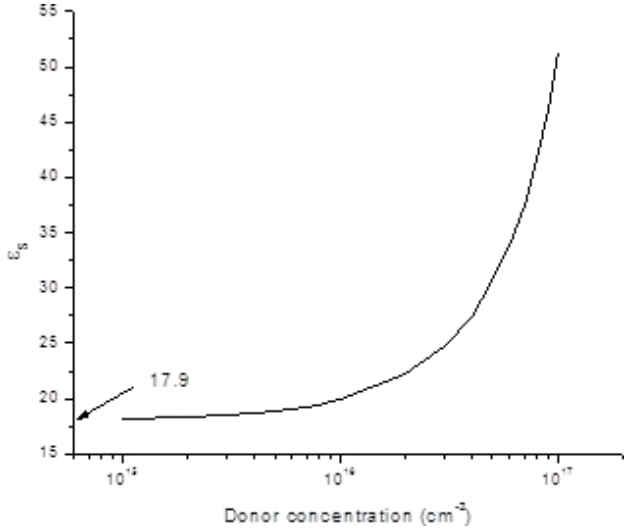

Figure 1: Variation of static dielectric constant with donor impurity concentration. The graph shows the results of calculations using equations 2 and 3 and data presented in Table 1.

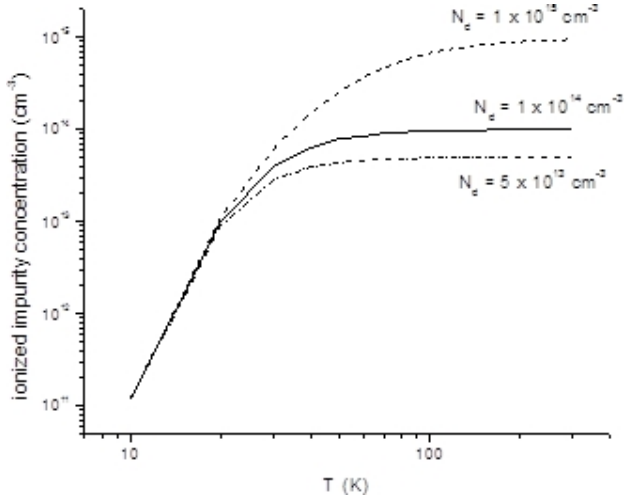

Figure 2: Variation of ionized donor concentration with temperature from 10-300 K. The graph shows the results of calculations using equations 9-12 and data presented in Table 1.

Using equations 4-15, one can obtain that the ionized donor concentration, the donor ionization energy as well as the mobility due to different types of scattering, are all dielectric permittivity dependent. Fig. 2 shows the variation of the ionized impurity concentration as a function of temperature at different values of donor concentration (and consequently static dielectric permittivity). The ionized impurity concentration was calculated from equations 9-13 and the parameters presented in table1. From Fig. 2, as the temperature grows, the number of ionized donors increases till it reaches saturation at relatively high

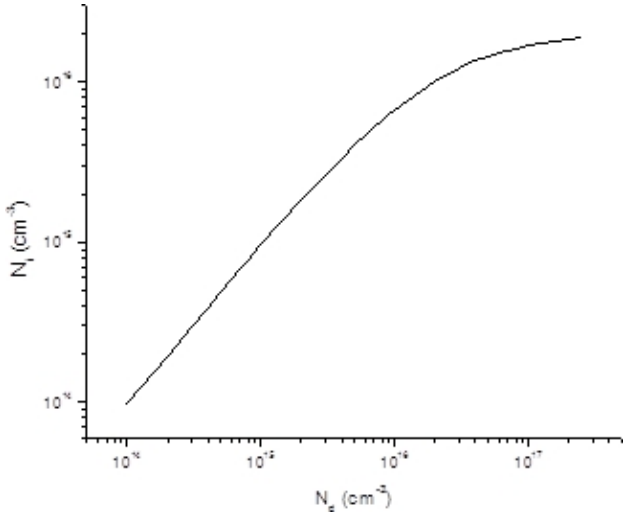

Figure 3: Ionized donor concentration versus donor concentration at 300 K. The graph is due to calculations of equations 9-12 and data presented in Table 1.

temperatures (greater than approximately 90 K in the case of InSb).

The concentration of the ionized impurities was also studied as a function of donor concentration at 300 K (Fig. 3). As expected, when the donor concentration increases, the number of ionized donors increases.

Fig. 4 represents a plot of carrier concentration versus temperature at donor concentration of 10^{14} cm^{-3}. Carrier density was calculated from the relations [10];

$$n = \frac{N_i}{2} + \sqrt{\frac{N_i^2}{4} + n_i^2} \tag{16}$$

$$n_i = \sqrt{N_c N_V} \exp\left[\frac{-E_g}{2kT}\right] \tag{17}$$

where E_g is the width of the forbidden gap and N_V is the density of the valence band states. The dashed line represents calculation of the intrinsic carriers density from the equation 17. Three regions appear in the graph. Above nearly 150 K intrinsic behavior is noticed. By lowering down the temperature till approximately 40 K, a constant carriers density is recorded. Freeze out region is then noticed at temperatures lower than 40 K.

The dependence of the donor ionization energy (the distance between donor energy level and the bottom of the conduction band) on the concentration of donors at 300 K is shown in Fig. 5. The ionization energy starts with the value of 0.6 meV at low donor concentrations and decreases slightly by increasing of the donor concentration before rapid decreasing. The slight initial decrease may be due to formation of impurity band and by further increas-

ing the donors, this band probably mergs with the bottom of the conduction band causing band tailing [12].

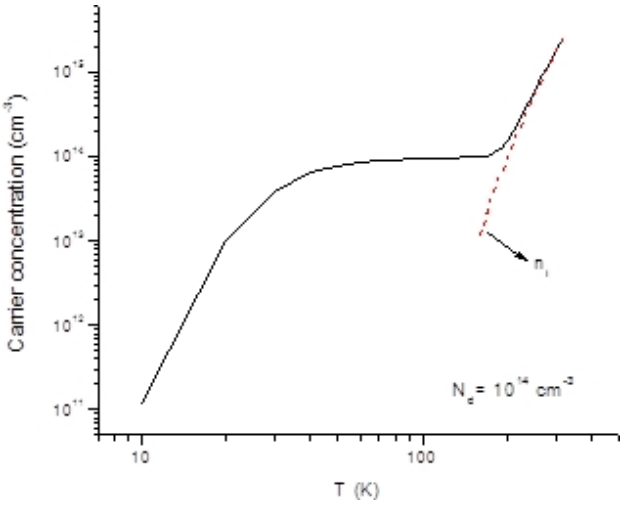

Figure 4: Carrier concentration versus temperature from 10-300 K. the donor concentration is fixed at 10^{14} cm^{-3}. The graph is due to calculations of equations 16 and 17 and data presented in Table 1.

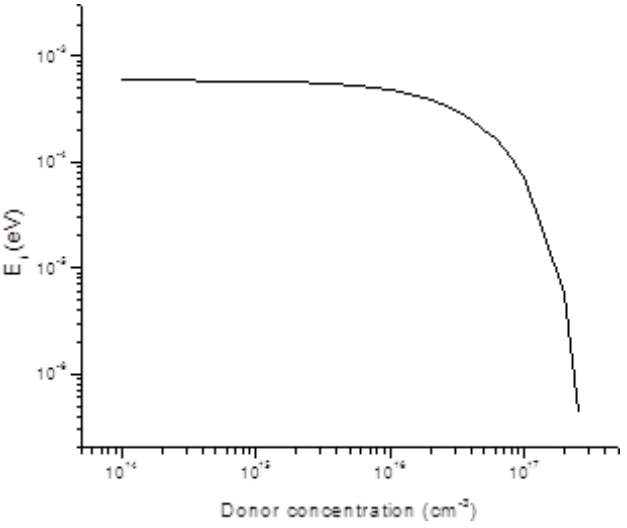

Figure 5: Dependence of the donor ionization energy on the donor concentration at 300 K. The graph is due to calculations of equations 13, 2 and 3 with the data presented in Table 1.

The electron mobility due to different types of scattering mechanisms was calculated using equations 4-15 and equations 2 and 3. Fig. 6 demonstrates the temperature dependence of the electron mobility from 10 K up to 300 K at three values of the donor concentration. Generally, the electron mobility shows peak behavior in this range of temperatures. The peak mobility recorded at N_d =

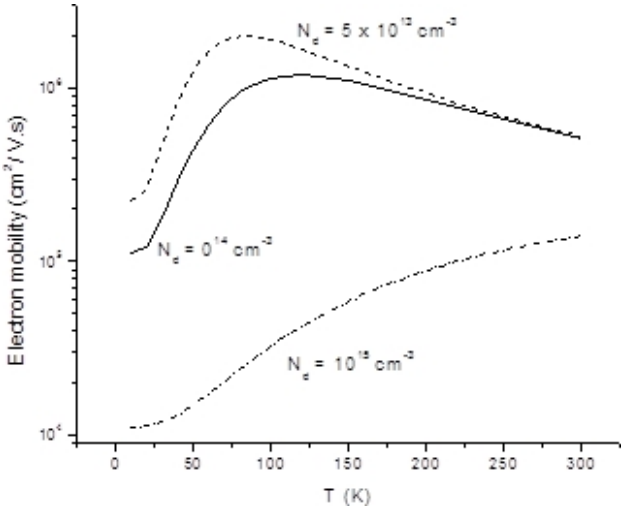

Figure 6: Temperature dependence of the electron mobility from 10-300 K. The graph is due to calculations using equation 15 simulated with equations 4-14 and data presented in Table 1.

5×10^{13} cm^{-3} is 2×10^6 cm^2/V.s while it is 1.2×10^6 cm^2/V.s at $N_d = 10^{14}$ cm^{-3}. The room temperature mobility is about 5.3×10^5 cm^2/V.s. The direct correlation between the electron mobility and the static dielectric permittivity at 300 K can be understood from Fig. 7.

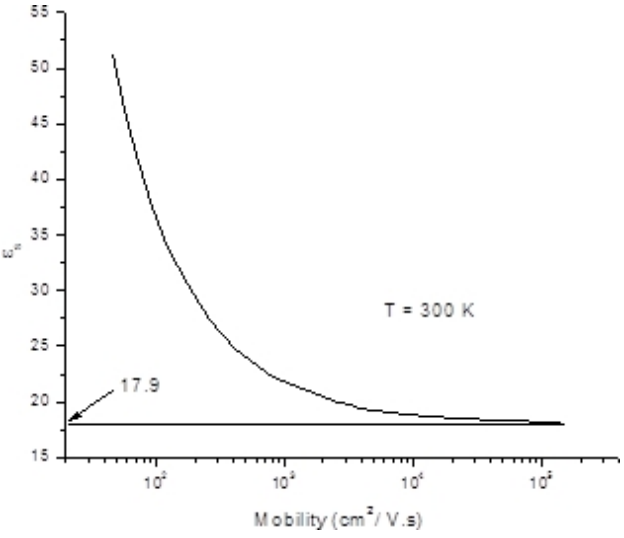

Figure 7: The relationship between the electron mobility and the static dielectric constant at 300 K. The graph is due to calculations of equations 3-15 and data presented in Table 1.

Another way to combine the electron mobility and the static dielectric permittivity is to study the dependence of the mobility on the donor concentration. Fig. 8 demonstrates this dependence when the static dielectric permittivity is assumed to be varying (solid curve) and when it

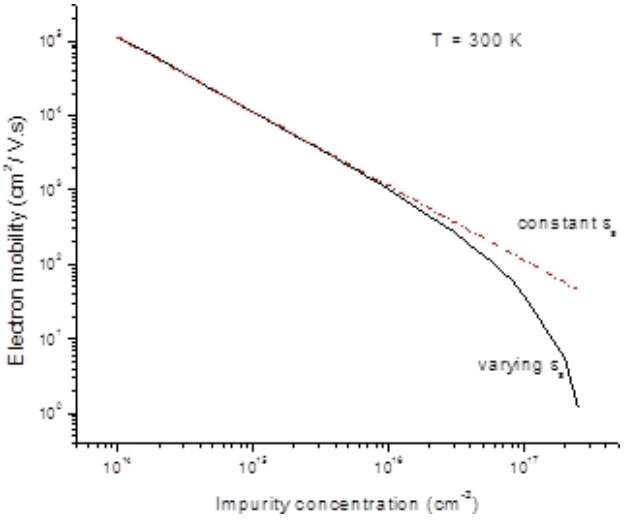

Figure 8: The dependence of the electron mobility on the doping concentration at 300 K. The graphs are due to calculations of equations 3-15 at constant temperature and data presented in Table 1. The solid curve considering the static dielectric constant as donor dependent while the dashed curve considers it as constant value.

is assumed to be constant (dashed curve). At low doping level until approximately 10^{16} cm^{-3}, there is no difference between the two curves indicating that it is possible to consider the static dielectric permittivity as non-varying parameter. Above 10^{16} cm^{-3} the two curves are different indicating that it is important to consider the dependence of the static dielectric permittivity on the doping concentration in all mobility calculations.

4 Conclusions

The electron mobility and the static dielectric permittivity for n-type InSb were calculated using direct numerical methods. The variation of the static dielectric permittivity with donor concentration indicated that as the number of donor increases, the produced polarization may cause increase in the static dielectric permittivity until a value at which polarization catastrophe may happen and hence the static dielectric permittivity tends to infinity. The mobility results showed peak behavior at temperature around 70 K. The dependence of the electron mobility on the donor concentration was demonstrated when the static dielectric permittivity was assumed to be varying and when it is assumed to be constant. It was concluded that it is important to consider the dependence of the static dielectric permittivity on the doping concentration in the mobility calculations above doping level of 10^{16} cm^{-3}.

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