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Low-temperature electronic transport in CdSe single quantum wells

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Abstract . Mobility and magnetoresistance of the two dimensional electrons in CdSe single quantum wells (SQWs) are calculated in the temperature range of 4.2K–30K incorporating deformation potential acoustic, piezoelectric, and background and remote ionized impurity scatterings using Fermi-Dirac statistics. The mobility agrees with the available experimental result at 4.2K, and is found to be limited mainly by the ionized impurity scattering in the temperature range considered. The magnetoresistance coefficient is found to be more sensitive than the mobility to the changes in the channel width, the background impurity concentration and the magnetic field.

Keywords Mobility, magnetoresistance, single quantum wells (SQWS)

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1. Introduction

ZnTe/CdSe single quantum wells (SQWs) have received considerable attention in recent years due to their scientific importance and technological applications [1-3]. In particular, such quantum wells are used in optoelectronic devices like lasers [2]. The widths of the QWs being comparable to the de Broglie wavelength, electron motion is quantized in the direction perpendicular to the layers. A sub-band structure of electron energy levels is thus formed resulting in the two-dimensional (2D) transport parallel to the interface. Theoretical studies of the 2D electronic transport in CdSe SQWs are scarce in the literature although some experimental data are available [3].

In this paper, we investigate theoretically the transport properties of the 2D electron gas in CdSe SQWs incorporating Fermi-Dirac statistics and the relevant scattering mechanisms in the temperature range of 4.2K to 30K. Such low temperatures are desirable for low noise and small energy spread of the electrons responsible for transport [4]. The variations of the electron mobility and the magnetoresistance coefficient with the width of the QW, the impurity concentration and the magnetic field in the non-quantizing limit, are reported herein.

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2. Theoretical background

The energy band diagram of the ZnTe/CdSe SQW is shown in Figure 1. Similiar to GaAs QWs, we assume that for the ZnTe/CdSe SQW system, the conduction band (CB) offset ΔE_c is 60% of the difference of the band gaps which are 2.34eV for ZnTe and 1.75eV for CdSe. Accordingly, ΔE_c for the ZnTe/CdSe system is about 0.36eV, which is 16 times the Fermi energy (0.022eV) of the electrons of concern here. The square well can thus be taken to be infinite. Furthermore, the energy difference between the lowest sub-band and the next higher one is found

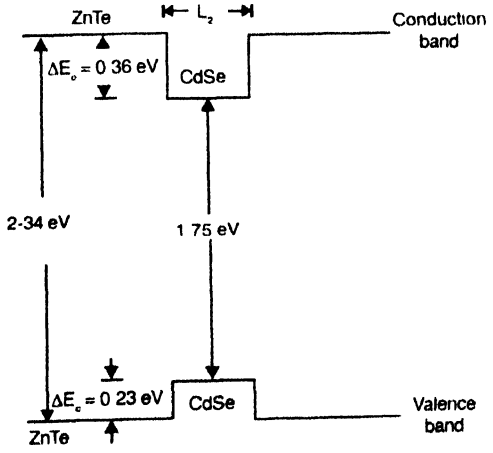

Figure 1. Energy band diagram of ZnTe/CdSe SQW

to be 0.08eV which is about 4 times the Fermi energy. So the electrons can be assumed to occupy the lowest sub-band only in our calculations.

We consider a rectangular Cartesian coordinate system with z-axis perpendicular to the interfacial planes so that the 2D transport occurs parallel to the xy plane. The electric field ε is assumed to be along x-axis and the non-quantizing magnetic field B along z-axis. The carrier distribution function can be written as

$$f(k) = f_0(E) - \left(\frac{e\hbar}{m^*}\varepsilon\right)\frac{\partial f_0}{\partial E}\left[k_x\xi_x(E) - \omega_B k_y \xi_y(E)\right], \quad (1)$$

where k is the 2D wave vector of electrons with energy $f_0(E)$ is the equilibrium Fermi-Dirac function, e is the electronic charge, $\hbar$ is Planck's constant divided by 2π, m^* is the electron effective mass, k_x and k_y are the x- and y-components of k, $\omega_B = \frac{eB}{m^*}$ is the cyclotron resonance frequency, and ξ_x and ξ_y are the perturbation functions. We consider here, deformation potential acoustic, piezoelectric, and ionized (both remote and background) impurity scatterings. The longitudinal optic (LO) phonon scattering is not included since LO phonon temperature for CdSe is 303K, and so the LO phonons do not contribute significantly up to 30K, the highest temperature considered here [5].

The perturbation functions obtained from the Boltzmann transport equation are

$$\xi_x(E) = -\frac{\tau(E)}{1+\omega_B^2\tau^2(E)} \quad (2)$$

and

$$\xi_y(E) = \frac{\tau^2(E)}{1+\omega_B^2\tau^2(E)}. \quad (3)$$

Here, $\tau(E)$ is the combined relaxation time for all the scatterings:

$$\tau^{-1}(E) = \tau_{ac}^{-1}(E) + \tau_{\perp p}^{-1}(E) + \tau_{//p}^{-1}(E) + \tau_{im}^{-1}(E), \quad (4)$$

where $\tau_{ac}(E)$ is the relaxation time for deformation potential acoustic scattering, $\tau_{\perp p}(E)$ and $\tau_{//p}(E)$ are those for the piezoelectric scattering of perpendicular and parallel modes, respectively. $\tau_{im}(E)$ is the relaxation time for background and remote impurity scatterings. The expression for $\tau_{ac}(E)$ is taken from Ref.[6], while that for $\tau_{im}(E)$ is taken from Ref.[7]. The expression for relaxation time of piezoelectric scattering is given in Ref.[6]. For the sphalerite structure, the piezoelectric coefficient is isotropic; but for the wurtzite structure, it is anisotropic. So, there are two piezoelectric relaxation times: $\tau_{\perp p}$ and $\tau_{//p}$ for perpendicular and parallel modes, respectively. They correspond to different piezoelectric coefficients for the electric field perpendicular and parallel to the c-axis, respectively Ref.[5].

The Hall mobility μ_H and the magnetoresistance coefficient R_m are given by

$$\mu_H = \frac{\mu_{xx}(0)|\mu_{xy}}{B\left(\mu_{xx}^2 + \mu_{xy}^2\right)} \quad (5)$$

and $$R_m = \frac{\mu_H B\mu}{\mu_{xy}} \quad 1, \quad (6)$$

where

$$\mu_{xx} = \frac{e}{\pi N_{2D}\hbar^2}\int_0^\alpha\left(-\frac{\partial f_0}{\partial E}\right)\frac{\tau(E)}{1+\omega_B^2\tau^2(E)}E\,dE,$$

$$\mu_{xy} = \frac{e\omega_B}{\pi N_{2D}\hbar^2}\int_0^\alpha\left(-\frac{\partial f_0}{\partial E}\right)\frac{\tau^2(E)}{1+\omega_B^2\tau^2(E)}E\,dE \quad (8)$$

and the drift mobility $\mu_{xx}(0)$ is the value of μ_{xx} for $B = 0$

3. Results and discussion

The electron effective mass for CdSe including polaronic correction is taken as $m^*=0.12m_0$ [3]. In accordance with the experimental sample of Ref.[3] we take the 2D carrier concentration $N_{2D} = 4.8 \times 10/\text{m}^2$.

To study the variation of mobility with temperature, the width of the QW is taken to be 10.5nm as in the experimental sample of Ref.[3]. We adjust here the value of the background ionized impurity concentration N_I to $8.6 \times 10^{22}/\text{m}^3$ to fit the experimental mobility of 0.88 $\text{m}^2/(\text{V.s})$ at 4.2K[3]. The other parameter values for CdSe are taken from Ref. [5].

Figure 2(a) displays the variations with temperature, the mobilities limited by deformation potential acoustic scattering

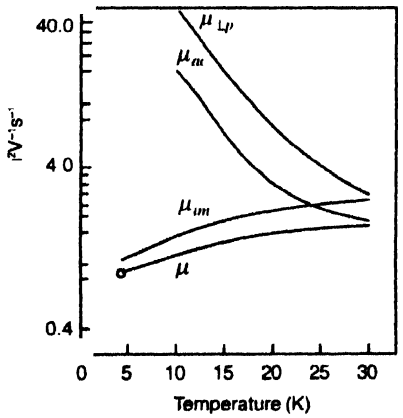

Figure 2(a). 2D electron mobility *vs.* Temperature in CdSe SQW for L = 10.5nm, $N_{2D} = 4.8 \times 10^{15}/\text{m}^2$, and $N_I = 8.6 \times 10^{22}/\text{m}^3$. μ_{ac}, $\mu_{\perp p}$, and μ_{im} represent respectively mobilities for deformation potential acoustic scattering, piezoelectric perpendicular mode scattering and ionized impurity scattering. μ is the overall mobility. The point represents experimental result.

(μ_{ac}), piezoelectric perpendicular mode scattering ($\mu_{\perp p}$) and ionized impurity scattering (μ_{im}). The variation of the overall mobility (μ) combining all these scattering mechanisms is also shown. Figure 2(b) gives the same variations except that $\mu_{\perp p}$ is replaced by $\mu_{\parallel p}$, the mobility limited by piezoelectric parallel mode scattering. As the phonon occupation number decreases with increasing temperature, μ_{ac}, $\mu_{\perp p}$ and $\mu_{\parallel p}$ drop off as the temperature increases. But μ_{im} increases with increasing temperature because of its Coulombic nature. The contribution from ionized impurity scattering is found to be dominant over the temperature range considered thus masking the anisotropic nature of the piezoelectric scattering in Figures 2(a) and (b).

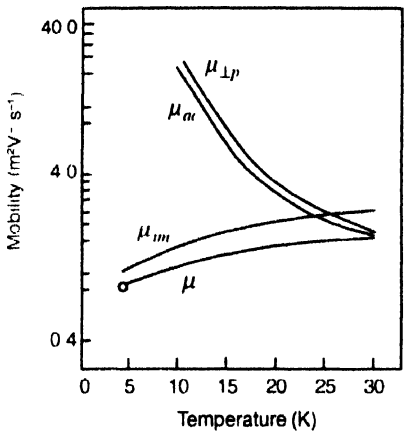

Figure 2(b). The same as in Figure2(a) with $\mu_{\perp p}$ replaced by $\mu_{\parallel p}$, the piezoelectric parallel mode scattering mobility. All the other quantities have the same meanings as in Figure 2(a).

Figure 3 shows variation of the overall mobility (μ) and the magnetoresistance (R_m) with channel width L_z for non-quantizing magnetic fields $B = 0.02$T and 0.08T and for $N_I = 8.6 \times 10^{22}/m^3$ and $N_{2D} = 4.8 \times 10^{15}/m^2$ at 4.2K. The Hall and drift mobilities are not distinguishable in our calculations, the Hall-to-drift mobility ratio being very close to unity. As L_z increases, the impurity

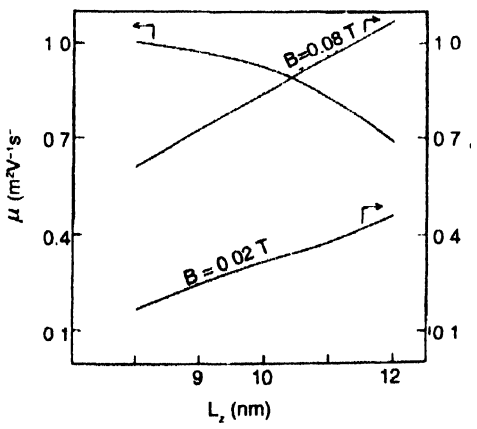

Figure 3. Overall mobility (μ) and magnetoresistance (R_m) against the channel width (L_Z) for magnetic fields B = 0.02T and 0 08T for N_I = 8 6 × $10^{22}/m^3$ and N_{2D} = 4.8 × $10^{15}/m^2$ at 4 2K.

scattering gets stronger [7]. Hence, μ decreases while R_m increases with increasing L_z. For the higher magnetic field $B = 0.08$T as compared to $B = 0.02$T, the increase of R_m with L_z is more prominent.

Figure 4 displays the variation of μ and R_m with N_I for L_z =10.5nm at 4.2K for B=0.02T and 0.08T. Due to the Coulombic nature of the ionized impurity scattering, μ decreases but R_m increases with increasing N_I. The effect on R_m is stronger for higher magnetic field.

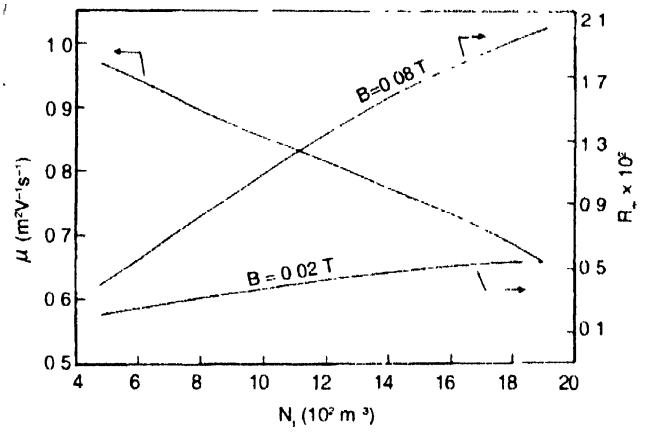

Figure 4. Variations of μ and R_m with N_I for L_z = 10 5nm at 4 2K for B = 0 02T and 0 08T

4. Conclusion

We show here the variations of mobilities due to acoustic, piezoelectric, and ionized (including both remote and background) impurity scatterings in CdSe SQW with temperature. We also give the variations of the mobility and the magnetoresistance coefficient with the channel width and the background impurity concentration. We find that the magnetoresistance coefficient is quite sensitive to the changes in B and the system parameters. Hence, experimental data on R_m are required for a better understanding of the 2D carrier transport in CdSe QWs.

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