Enhancement of low temperature electron mobility due to an electric field in an InGaAs/InAlAs double quantum well structure

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The effect of external electric field F on multisubband electron mobility μ in an $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{48}As$ double quantum well structure is analyzed. We consider scatterings due to ionized impurities, interface roughness and alloy disorder to analyze μ. The variation of scattering mechanisms as a function of F for different structure parameters shows interesting results through intersubband interactions. For small well widths, the mobility is governed by interface roughness scattering. When two subbands are occupied, the effect of impurity scattering gets enhanced through intersubband interactions. Our results of enhancement in mobility as a function of F, can be utilized for low temperature devices.

1. Introduction

$In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum well structure, lattice matched to InP substrate, has continued to draw attention as a potential material for high speed electronic and optoelectronic devices [1–3]. A double quantum well structure is an interesting system which exhibits tunneling coupling in addition to quantum confinement effect. Variation in the structure parameters such as well width, barrier width and doping concentration changes the subband energy levels and wave functions of the quantum well. By varying the structure parameters the occupation of subbands can be changed. For such systems where there is more than one subband is occupied, intersubband interaction plays a major role on the electron mobility [4–7]. A great deal of work has been done to study the multisubband electron mobility as a function of structure parameters of the quantum well systems [6–10]. In recent years attempts have also been made to study the influence of electric field on the electron mobility in quantum well structures [11–15]. The electric field affects the potential profile of the quantum well structure. As a result the subband energy levels and wave functions are changed which emends the electron mobility.

In the present work we analyse the electric field induced changes in the multisubband electron mobility in an $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ double quantum well structure. We consider symmetric scattering potentials: (i) ionized impurity (imp) scattering from the symmetrically placed delta-doped layers in the side barriers, (ii) interface roughness (IR) scattering from all the interfaces of the structure and (iii) alloy disorder (AL) scattering from the

wells as well as the barriers of the structure. We analyze the enhancement in electron mobility due to the effect of the external uniform electric field F, applied perpendicular to the interface plane, mediated by intersubband interactions. The effect of F alters the symmetric scattering potentials into asymmetric ones resulting interesting effects. We adopt the random phase approximation to obtain the screening of the scattering potentials [6,7,10] and analyze the influence of the electric field F on the scattering mechanisms by taking different well widths. In case of narrow well widths, the mobility is dominated by the IR scattering. We show that as long as the lowest subband is occupied, the electric field F has negligible effect on the subband mobility. However, with increase in well width, the second subband level starts occupying and the mobility gets influenced by the imp-scattering in addition to IR-scattering through the intersubband effects. Application of the electric field F causes transition from double subband occupancy to single subband occupancy, resulting enhancement in mobility due to the suppression of the intersubband scattering. At large well widths, the influence of IR-scattering gets reduced. It is interesting to note that with increase in F, the mobility due to the alloy disorder scattering μ^{AL} decreases and no discontinuity in mobility is seen at the transition from double subband to single subband occupancy because of negligible contribution of the intersubband scattering rate matrix elements. Therefore the enhancement in mobility, induced by the electric field, is mainly governed by the IR- and imp-scatterings in narrow well widths and imp-scattering for larger well widths. Further we show that as the well width increases the enhancement in mobility occurs at a lower field F. Our results can be utilized for low field device applications.

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2. Theory

We consider an $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ double quantum well structure. The side barriers (InAlAs layers) are delta-doped with a layer of width d and concentration N_0. The doping layers lie at a distance s from the corresponding interfaces. The wells (InGaAs layers) are of width w. The width of the central barrier is b. The both the wells and the central barrier are undoped. The electrons diffuse into the adjacent wells. The band bending occurs due to the electrostatic interaction of the diffused electrons and the ionized donors through the alignment of Fermi level in the system. The electrons are confined to two narrow strips separated by a thin central barrier forming a coupled two-dimensional electron gas 2DEG [4]. We obtain an analytical expression for the potential profile $V(z)$ along the growth direction, say z-axis, by solving the Poisson's equation and adopting variatiional trial wave function method [4,10]. We incorporated the conduction band offset, i.e., the potential barrier height V_b at the interfaces of the quantum well structure and also the effect of the external uniform electric field F in the potential energy profile of the structure. The bound subband energy levels E_n and wave functions $\Psi_n(z)$ are obtained numerically by using multistep potential method [10,16].

At temperature $T = 0$, the subband transport lifetime $\tau_n = \tau_n(E_{Fn})$ since only the electrons on the Fermi surface contribute to the transport. E_{Fn} is the Fermi level of the nth subband, $E_{Fn} = E_F - E_n$. The expression for multisubband transport life time τ_n can be derived using the Boltzmann equation [5,6] in which τ_n contains the intra-subband and inter-subband scattering processes. For lower subbands one can express them in simple forms [5,7,10]. For example for a single occupied band $(n = 0)$:

$$\frac{1}{\tau_0} = B_{00}. \tag{1}$$

For double occupied bands $(n = 0, 1)$:

$$\frac{1}{\tau_0} = \frac{(B_{00} + C_{01})(B_{11} + C_{10}) - D_{01}D_{10}}{(B_{11} + C_{10}) + (E_{F1}/E_{F0})^{1/2}D_{01}},$$

$$\frac{1}{\tau_1} = \frac{(B_{00} + C_{01})(B_{11} + C_{10}) - D_{01}D_{10}}{(B_{00} + C_{01}) + (E_{F0}/E_{F1})^{1/2}D_{10}}. \tag{2}$$

The intrasubband scattering rate matrix element B_{nn} and intersubband scattering rate matrix elements C_{nm} and D_{nm} are expressed in terms of the matrix elements of screened scattering potentials $V_{nm}^{\text{eff}}(q)$ as [10]

$$B_{nn} = m/(\pi\hbar^3) \int_0^\pi d\theta(1 - \cos\theta) \left|V_{nn}^{\text{eff}}(q_{nn})\right|^2,$$

$$C_{nm} = m/(\pi\hbar^3) \int_0^\pi d\theta \left|V_{nm}^{\text{eff}}(q_{nm})\right|^2,$$

$$D_{nm} = m/(\pi\hbar^3) \int_0^\pi d\theta \cos\theta \left|V_{nm}^{\text{eff}}(q_{nm})\right|^2, \tag{3}$$

$$q_{nl} = [k_{Fn}^2 + k_{Fl}^2 - 2k_{Fn}k_{Fl}\cos\theta]^{1/2}, \quad k_{Fn} = (2mE_{Fn}/\hbar^2)^{1/2}.$$

We consider non phonon scattering mechanisms i.e., ionized impurity scattering, interface roughness scattering and alloy disorder scattering. The screened ionized impurity potential can be written as [10]:

$$\left|V_{nm}^{\text{imp}}(q)\right|^2 = \frac{4\pi^2 e^4 N_0}{\varepsilon_0^2 q^2}$$

$$\times \left[\int_{-(b/2+w+s+d)}^{-(b/2+w+s)} dz_i \left| \sum_{n'm'} \varepsilon_{nm,n'm'}^{-1}(q) P_{n'm'}(q, z_i) \right|^2 \right.$$

$$\left. + \int_{(b/2+w+s)}^{(b/2+w+s+d)} dz_i \left| \sum_{n'm'} \varepsilon_{nm,n'm'}^{-1}(q) P_{n'm'}(q, z_i) \right|^2 \right] \tag{4}$$

where

$$P_{n'm'}(q, z_i) = \int_{-\infty}^\infty dz \Psi_{n'}(z)\Psi_{m'}(z)e^{-q|z-z_i|}. \tag{5}$$

Similarly the screened alloy scattering potential and interface roughness scattering potential can be written as:

$$\left|V_{nm}^{\text{Al}}(q)\right|^2 = \sum_j [a_j^3(\delta V_j)^2 x_j(1 - x_j)/4]$$

$$\times \int_j dz \left| \sum_{n'm'} \varepsilon_{nm,n'm'}^{-1}(q) \Psi_{n'}(z)\Psi_{m'}(z) \right|^2, \tag{6}$$

$$\left|V_{nm}^{\text{IR}}(q)\right|^2 = V_b^2 \pi \Lambda^2 \Delta^2 e^{-q^2\Lambda^2/4}$$

$$\times \sum_{bi} \left| \sum_{n'm'} \varepsilon_{nm,n'm'}^{-1}(q) \Psi_{n'}^*(z)\Psi_{m'}(z)|_{z=z_{bi}} \right|^2. \tag{7}$$

$\varepsilon_{nm,n'm'}^{-1}$ is the inverse of the dielectric screening matrix which can be expressed within the random phase approximation (RPA) as [4–7,10]:

$$\varepsilon_{nm,n'm'}(q) = \delta_{nn'}\delta_{mm'} + (q_s/q)F_{nm,n'm'}(q)\chi_{n'm'}^0(q), \tag{8}$$

where $q_s = 2me^2/\varepsilon_0\hbar^2$, F is the Coulomb form factor and χ is the static electron density — density correlation function without electron-electron interaction [4].

The ionized impurity scattering occurs from the two delta-doped layers lying in the side barriers. The alloy disorder scattering is considered from the well (InGaAs) regions as well as the barrier regions (InAlAs). Summation j is over all the layers of the structure. a_j is the lattice constant, δV_j is the alloy scattering potential and x_j is the alloy fraction of the jth layer. Δ is the mean height and Λ is the correlation length of the roughness of the interfaces. The interface roughness is assumed to exist equally in all the four interfaces of the structure [17], unlike the other quantum well structures where the roughness is assumed to be in the bottom interfaces i.e., substrate side [8,18]. Sum
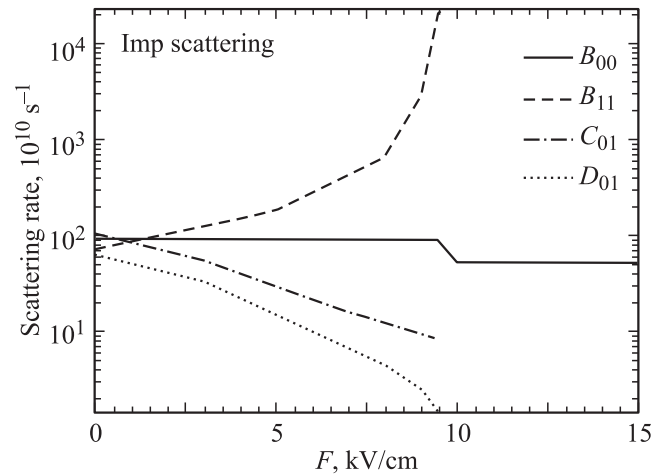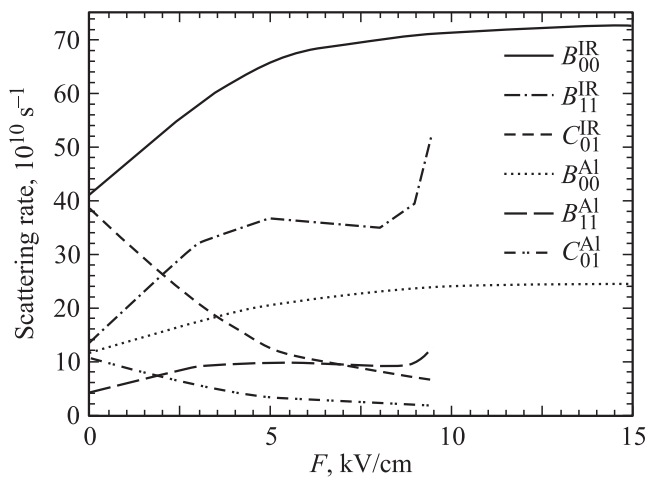
Figure 3. Intrasubband and intersubband scattering rate matrix elements for IR- and Al-scatterings as functions of F in kV/cm for $w = 80\,\text{Å}$.
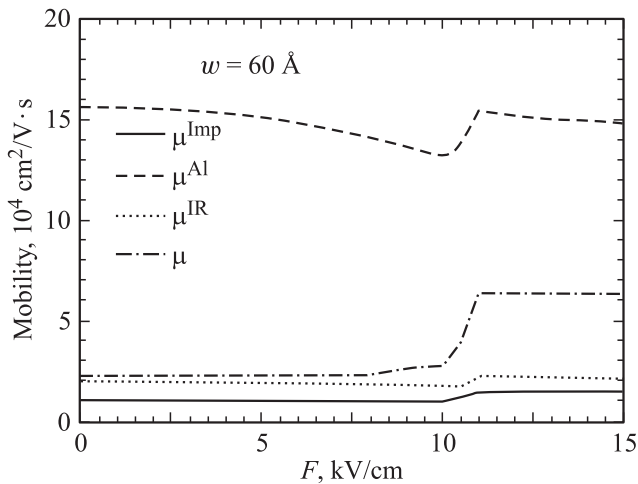

Figure 4. Mobility as a function of the electric field F for well width $w = 60\,\text{Å}$.

than μ^{IR}, so long as single subbnd is occupied. However, once double subband is occupied, the trend is reversed, $\mu^{\text{imp}} < \mu^{\text{IR}}$ due to the additional effect of the intersubband interaction. As w increases further (Fig. 5), the influence of IR-scattering becomes very less on mobility.

The influence of AL-scattering on mobility is interesting. Although it has a negligible contribution compared to other scattering mechanisms, the influence of AL-scattering on mobility enhances with increase in F. Furthermore, as the well width increases, the magnitude of sudden rise in μ^{Al} and μ^{IR} at the point of transition from double subband to single subband occupancy diminishes. In fact for $w = 120\,\text{Å}$ there is almost no discontinuity in mobility. This is because of the fact that the intersubband scattering rate matrix elements C_{01} and D_{01}, which are comparable in magnitude with that of the intrasubband scattering rate matrix element B_{00} for small well widths (say, $w = 60\,\text{Å}$), reduce to negligible values for large well widths ($120\,\text{Å}$)

Figure 5. Mobility as a function of the electric field F for well width $w = 120\,\text{Å}$.

We wish to study the effect of the electric field F on mobility by changing the well widths. In Figs. 4 and 5 we present μ^{imp}, μ^{IR}, μ^{Al} and μ taking well widths $w = 60$ and $120\,\text{Å}$ respectively. We note that for w less than $60\,\text{Å}$ (say $40\,\text{Å}$), only the lowest subband is occupied and the mobility is dominated by the IR scattering. As the well width increases, say for $w = 60\,\text{Å}$, as in Fig. 4, the second level is occupied at $F = 0$ and the imp-scattering influences the mobility more through intersubband interaction. As a result, the imp-scattering and IR-scattering almost equally influence the mobility. A sudden rise in mobility is obtained at the transition from double subband occupancy to single subband occupancy due to the suppression of the intersubband effects. Then the mobility is mostly influenced by the IR-scattering. With increase in w, say at $w = 80\,\text{Å}$ (Fig. 1), the influence of imp- and IR-scatterings on mobility decreases unequally and as a result the difference between μ^{imp} and μ^{IR} becomes less μ^{imp} being greater

Figure 6. Comparison of total mobility μ as a function of electric field F for different well widths, $w = 40, 60, 80, 100, 120, 140$ and $160\,\text{Å}$ as written within the parenthesis in the figure.

near the point of transition from double subband to single subband occupancy. The continued drop in μ^{Al} and μ^{IR} are due to the continuous rise in B_{00} for AL- and IR-scatterings as seen from Fig. 3.

In Fig. 6, we present the total mobility μ as a function of the electric field F for different well widths, $w = 40, 60, 80, 100, 120, 140$ and $160\,\text{Å}$. For $w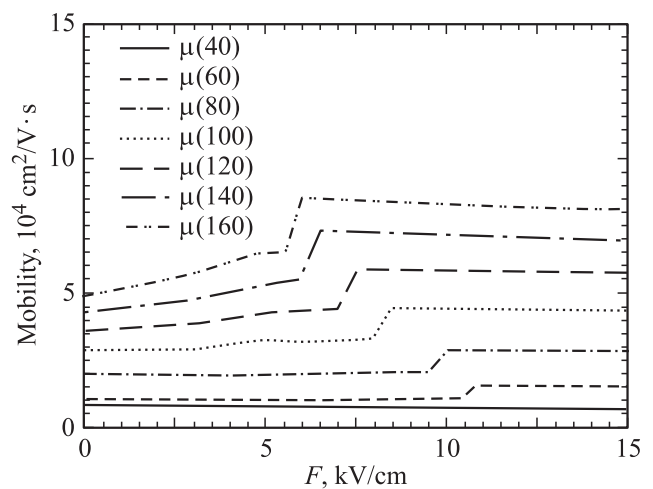 = 40\,\text{Å}$ single subband is occupied. For $w = 60\,\text{Å}$ and onwards, two subbands are occupied at $F = 0$. Transition from double subband to single subband occupancy occurs at a field, say F_t, leading to enhancement of mobility due to containment of intersubband effects as discussed earlier. It is gratifying to show that the value of F_t decreases with increase in the well width. It would be interesting to compare our results of electric field dependent mobility with the experimental results when they will be available.

4. Conclusion

To summarize, we analyze the effect of external electric field on the low temperature multisubband electron mobility in an $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ double quantum well structure. We have considered non-phonon scattering mechanisms, viz., impurity scattering, interface roughness scattering and alloy disorder scattering. The influence of the electric field perpendicular to the interface plane alters the potential profile of the structure leading to changes in the electron subband energy levels and wave functions which affect the screened scattering potentials. With increase in the electric field the system undergoes transition from double subband to single subband occupancy resulting enhancement of mobility due to the absence of the intersubband effects. We analyse the changes in the electron mobility induced by the electric field by taking different well widths and show that for larger well widths the mobility enhances at a lower field. Our results of the mobility for the coupled quantum well structure can be utilized for low temperature device applications.

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