Electron nonelastic scattering by confined and interface polar optical phonons in a modulation-doped AlGaAs/GaAs/AlGaAs quantum well

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The calculations of electron scattering rates by polar optical(PO) phonons in an AlGaAs/GaAs/AlGaAs quantum well (QW) with a different width and doping level are performed. The electron–PO-phonon scattering mechanisms which are responsible for the alternate dependence of electron mobility on a QW width, as well as for the decrease of conductivity in the QW with increasing sheet electron concentration are determined. It is shown that the enhancement of the scattering rate by PO-phonon absorption when the lower subband electron gas is degenerated is responsible for the decrease of QW conductivity with increasing sheet electron concentration. The competition between the decrease of the intrasubband scattering and the increase of the intersubband scattering by PO-phonon absorption is responsible for the alternate changes of the mobility with a QW width.

Introduction

The alternate change (increase and decrease) of electron mobility as a function of quantum well (QW) width and doping level in modulation-doped AlGaAs/GaAs and AlGaAs/InGaAs QW's was recently observed [1–3]. The predominant mechanism which determines the electron mobility in modulation-doped GaAs QW at $T > 77$ K is electron scattering by confined and interface polar optical (PO) phonons.

In this paper the separate contribution to electron mobility of definite type intra- and intersubband electron transitions with absorption or emission of PO phonons is considered. The scattering mechanisms which are responsible for alternate mobility changes with a QW width and doping level are determined.

1. Confined electron–PO-phonon scattering rate and mobility in $Al_{0.25}Ga_{0.75}As/GaAs/Al_{0.25}Ga_{0.75}As$ quantum wells

The transition frequency of electrons, confined in a quantum well (QW), from an initial state in subband i with momentum $\mathbf{k}_i$ and subband electron energy E_{si}, to any final state, $\mathbf{k}_f$, E_{sf}, in subband f by emission (absorption) of ν-mode PO-phonon can be written as [4–7]

$$\mathbf{w}^{a,e}_{if\nu}(k_i, E_{si}) = \sum_{\mathbf{k}_f} \frac{4\pi m e^2}{\hbar^3} |G_\nu|^2 F^2_{q\nu} \left(N_{q\nu} + \frac{1}{2} \pm \frac{1}{2} \right) \times \delta\left(\mathbf{k}_f^2 - \mathbf{k}_i^2 + \beta_\pm\right), \quad (1)$$

where G_ν is the overlap integral of the normalized electron and phonon wave functions, $N_{q\nu}$ is the occupation number of ν-mode phonons, and $\beta_\pm = \frac{2m}{\hbar^2}(E_{sf} - E_{si} \pm \hbar\omega_\nu)$. The upper sign (plus) is for phonon emission and the lower (minus) one is for phonon absorption. The phonon potentials and their interaction intensity with electrons ($F^2_{q\nu}$) are calculated by using the dielectric continuum model [7,8].

The electron–PO-phonon scattering rates were calculated at $T = 100$ K for the symmetric rectangular $Al_{0.25}Ga_{0.75}As/GaAs/Al_{0.25}Ga_{0.75}As$ QW with sheet electron concentration in the range of $5 \cdot 10^{15} < n_s < 6 \cdot 10^{16}\,\mathrm{m}^{-2}$ and QW widths $15 < L < 35$ nm. The parameters used in the calculations were: $m/m_0 = 0.67$, $\hbar\omega_0 = 36.2$ meV, $\chi_\infty = 10.9$, $\chi_s = 12.9$ for GaAs and $m/m_0 = 0.09$, $\hbar\omega_0 = 46.8$ meV, $\chi_\infty = 10.1$, $\chi_s = 13.0$ for AlGaAs. The $Al_{0.25}Ga_{0.75}As/GaAs$ barrier is assumed $U_0 = 0.3$ eV.

The nonelastic electron–PO-phonon scattering with a large change of scattered electron energy requires to take into account the different occupation of electrons in the initial and final states. Taking into account the electron state occupation, the mean frequency of electron transitions (scattering rates) from the initial state in subband i to the final one in subband f can be written in the form

$$W^{a,e}_{if} = \sum_\nu \int_{E_{si}}^{\infty} w^{a,e}_{if\nu}(E) \, \frac{1 - f(E \pm \hbar\omega_\nu)}{1 - f(E)} \, dE \Bigg/ \int_{E_{si}}^{\infty} f(E)\, dE, \quad (2)$$

where $f(E)$ is the electron Fermi–Dirac distribution function, and the plus sign is for phonon absorption and the minus one is for phonon emission.

The electron mobility in pure GaAs at $T > 77$ K is determined by electron–PO-phonon scattering. In this paper the estimation of the separate contrubution to electron mobility of various type electron–PO-phonon scattering is done assuming the inverse mean frequency of electron transitions by PO-phonon absorption (emission) as a momentum relaxation time

$$\tau_{if} = 1/W_{if}. \quad (3)$$

This relaxation time approximation gives only a crude estimation of the mobility limited by PO-phonon scattering, but it is expected that this approximation is sufficient both for estimation of relative difference between the mobilities in QW's with different widths and sheet electron concentrations and for estimation the relative contribution to electron mobility of various electron scattering mechanisms by various phonon modes. Note that the values of mobility calculated within the used relaxation time approximation in the GaAs QW are near to the values observed experimentally.

In this approximation, the i-subband electron mobility is

$$\mu_i = \frac{e}{m} \Big/ \sum_f (W^e_{if} + W^a_{if}), \tag{4}$$

and the total electron mobility in the QW is

$$\mu = \frac{1}{n_s} \sum_i \mu_i n_i, \tag{5}$$

where n_s and

$$n_i = \frac{m}{\pi\hbar^2} \int\limits_{E_{si}}^{\infty} f(E)\, dE \tag{6}$$

are the sheet electron concentrations in the QW and in subband i, respectively.

2. The dependence of electron subband mobility on sheet electron concentration

The calculated intra- and intersubband electron–PO-phonon scattering rates as functions of sheet electron concentration n_s in the $Al_{0.25}Ga_{0.75}As/GaAs/Al_{0.25}Ga_{0.75}As$ QW of width $L = 20$ nm are presented in Fig. 1, a.

The significant enhancement of the intra- and intersubband scattering rates by PO-phonon absorption with increasing n_s is observed in the lower subbands ($W^a_{11}, W^a_{12}, W^a_{22}$). The enhancement takes place in the subbands with degenerate electron gas. This is largest in the lowest (first) electron subband (W^a_{11}), where the electron gas is most degenerated (see Fig. 1, a). On the contrary, the scattering rates by phonon emission from the upper subband to the lower one ($W^e_{31}, W^e_{32}, W^e_{21}$) decrease with electron gas degeneration in the lower subband. The scattering rate by phonon emission in the lower subband can be neglected.

The increase of scattering rates by PO-phonon absorption (W^a_{11} and W^a_{12}) is responsible for the strong decrease of electron mobility in the lowest (first) electron subband, μ_1, with increasing n_s, as it is shown in Fig. 1, b. The second subband mobility μ_2 increases due to decreasing the second subband electron scattering by phonon emission when n_s changes in the range of $(5-15) \cdot 10^{15}\,\mathrm{m}^{-2}$. At $n_s > 15 \cdot 10^{15}\,\mathrm{m}^{-2}$, μ_2 decreases very fast because of the strong increase of electron scattering rates $W^a_{22}, W^a_{21}, W^a_{23}$ by phonon absorption. The contribution of the second subband electrons to the total QW mobility increases with increasing second subband electron population.

This decrease of the mobilities in the first and second subbands exceeds the increase of n_s in the range of $(2-3) \cdot 10^{16}\,\mathrm{m}^{-2}$. As a result, the decrease of QW conductivity (μn_s) with increasing n_s takes place. This is shown in Fig. 1, b. When $n_s > 3 \cdot 10^{16}\,\mathrm{m}^{-2}$, the third subband electrons with the increased mobility, due to the decrease of W^e_{31}, W^e_{32}, gives the enhancement of the total QW conductivity in spite of decreasing the first and second subband mobilities.

The increase of μ_3 is limited at $n_s > 4.5 \cdot 10^{16}\,\mathrm{m}^{-2}$ due to the increase of electron scattering by phonon absorption in the third subband, and the second decrease of the conductivity μn_s is observed (Fig. 1, b).

It is worth noting that the electron mobility in the second subband exceeds two times the first subband mobility at $n_s = 1.5 \cdot 10^{16}\,\mathrm{m}^{-2}$. There are two types of electrons in the QW: low mobility electrons in the first subband and two times faster electrons in the second subband. At $n_s > 3 \cdot 10^{16}\,\mathrm{m}^{-2}$, the faster electrons are in the third subband (see Fig. 1, b).

Therefore, for the mobility decrease with increasing n_s in the $Al_{0.25}Ga_{0.75}As/GaAs/Al_{0.25}Ga_{0.75}As$ QW, the increase of the intra- and intersubband scattering rates by PO-phonon absorption in degenerate electron gas is responsible. For the alternate increase of conductivity, the decrease of the intersubband scattering by PO-phonon emission in the upper subbands, $W^e_{31}, W^e_{32}, W^e_{21}$, is responsible (because of electron gas degeneration in the lower subbands).

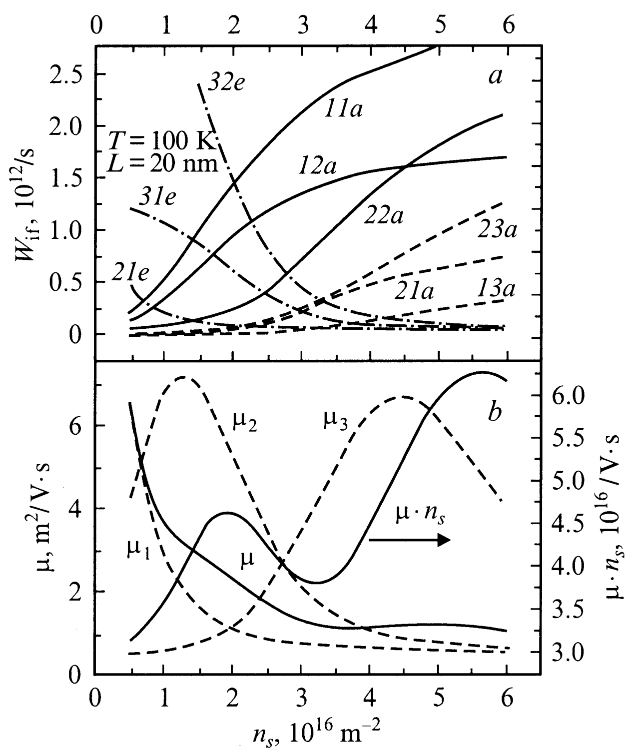

Figure 1. The electron–PO-phonon scattering rates W_{if} with electron transitions from the initial state in subband i to the final one in subband f by phonon emission and absorption (labeled by ife and ifa, respectively) (a) and the electron mobilities in subbands $i = 1, 2, 3$ (labeled by μ_1, μ_2, μ_3), the total mobility μ and conductivity ($\mu \cdot n_s$) (b) as functions of sheet electron concentration n_s in the QW of width $L = 20$ nm.

3. The dependence of electron mobility on a QW width

Fig. 2, *a* shows the QW width dependencies of electron intra- and intersubband scattering rates in the $Al_{0.25}Ga_{0.75}As/GaAs/Al_{0.25}Ga_{0.75}As$ QW at sheet electron concentration $n_s = 5 \cdot 10^{15}\,\mathrm{m}^{-2}$. At all QW widths in the range of $15 < L < 35$ nm, the main electron scattering mechanism in the lowest subband remains W_{11}^{a} and W_{12}^{a}. At $L > 18$ nm, the scattering rates W_{11}^{a} and W_{12}^{a} decrease slowly with increasing QW width. In the second and the third subbands, the intersubband transitions by PO-phonon emission are permitted and the scattering rates W_{31}^{e}, W_{32}^{e}, W_{21}^{e} are very high and exceed $10^{12}\,\mathrm{s}^{-1}$.

Such behavior of electron–PO-phonon scattering explains the alternate dependence of the mobility on GaAs QW width shown in Fig. 2, *b*.

We see that the increase of the first subband electron mobility μ_1 with increasing QW width L due to the decrease of W_{11}^{a} is limited at two QW widths: at $L = 15{-}18$ and $L = 25{-}30$ nm by the increase of the intersubband scattering rates W_{12}^{a}, and W_{13}^{a}, respectively. Between these two limited scattering (in the interval of $L = 18{-}25$ nm) the mobility monotonically increases with a QW width L.

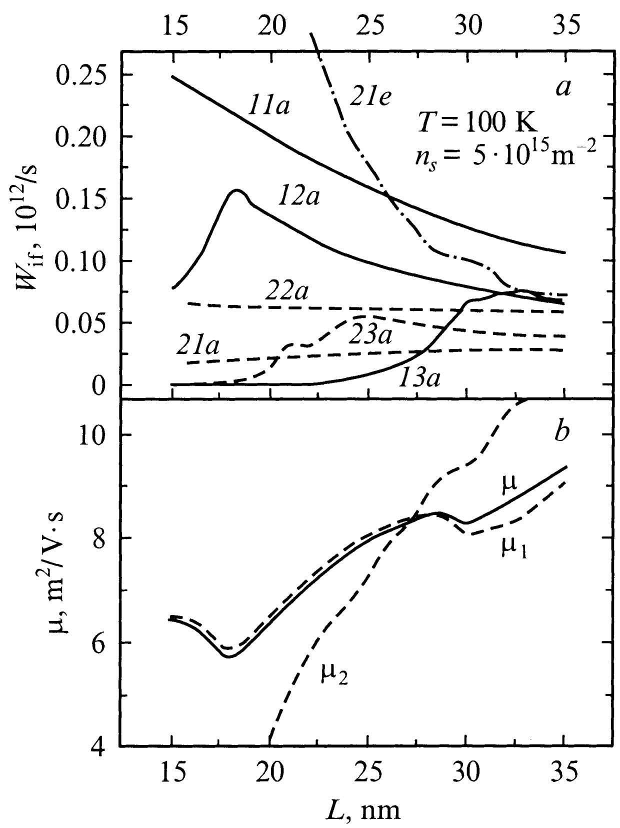

Figure 2. The electron–PO-phonon scattering rates W_{if} (*a*) and the subband and total electron mobilities (*b*) as functions of QW width at $n_s = 5 \cdot 10^{15}\,\mathrm{m}^{-2}$. Notations are as in Fig. 1.

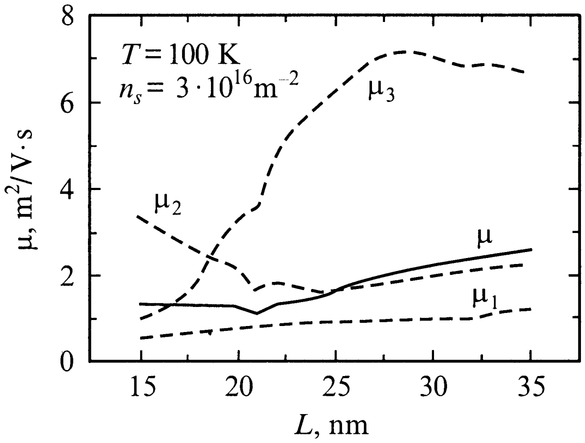

Figure 3. The subband and total electron mobilities as functions of QW width at $n_s = 3 \cdot 10^{16}\,\mathrm{m}^{-2}$. Notations are as in Fig. 1.

At QW widths $L = 15{-}25$ nm, the intersubband scattering rate with PO-phonon emission, W_{21}^{e}, decreases due to filing the electron states in the first subband. Therefore, the second subband electron mobility μ_2 increases. At $L > 27$ nm, μ_2 becomes larger than μ_1 (see Fig. 2, *b*).

When the sheet electron concentration in the QW increases until $n_s = 3 \cdot 10^{16}\,\mathrm{m}^{-2}$, the electron-phonon intersubband scattering rates changes significantly due to occupation of electron states in the lower subbands (see Fig. 1, *b*). This gives a ten times increase of the scattering rate by PO-phonon absorption in the lowest subband, W_{11}^{a}, and decrease of the scattering rate by PO-phonon emission in the upper subbands (see Fig. 1, *a*).

As a result, the electron mobility decreases strongly in the lower QW subband, and increases in the upper (third) subband. At $n_s = 3 \cdot 10^{16}\,\mathrm{m}^{-2}$, the population of electrons in the upper subbands is large, and their contribution to the total mobility is significant.

Fig. 3 shows the QW width dependence of electron mobilities at $n_s = 3 \cdot 10^{16}\,\mathrm{m}^{-2}$.

We see that the second subband electrons give the main contribution to the total mobility. The decrease of the mobility is observed only at $L = 22$ nm. It is explained by the increase of the scattering of second subband electrons to the third subband by phonon absorption (W_{23}^{a}). At $L > 22$ nm, the electron scattering rates in all subbands both with phonon emission and absorption decrease slowly with increasing a QW width. This circumstance gives the increase of the total mobility with increasing a QW width in the range of $22 < L < 35$ nm. Note that at $L > 25$ nm the third subband mobility is seven times larger than the mobility in the first subband.

Therefore, the total electron mobility increases with a QW width. This increase limits the electron intersubband scattering rates by phonon absorption: W_{12}^{a} and W_{13}^{a} in the QW with $n_s = 5 \cdot 10^{15}\,\mathrm{m}^{-2}$ and W_{23}^{a} in the QW with $n_s = 6 \cdot 10^{16}\,\mathrm{m}^{-2}$.

Conclusions

The electron–PO-phonon scattering mechanisms which are responsible for the dependencies of electron mobility on a QW width and doping level are determined. In is shown that:

1. The degeneration of subband electron gas decreases the electron scattering by PO-phonon emission and increases the scattering by phonon absorption. In the QW of width $L = 20\,\text{nm}$, the scattering by PO-phonon absorption exceeds the scattering by PO-phonon emission in the first subband at $n_s > 5 \cdot 10^{15}\,\text{m}^{-2}$, in the second subband at $n_s \geqslant 1.5 \cdot 10^{15}\,\text{m}^{-2}$ and in the third subband at $n_s \geqslant 4.5 \cdot 10^{15}\,\text{m}^{-2}$. At these n_s, the mobility in the upper subbands exceeds the mobility in the lower ones. The increase of the scattering by PO-phonon absorption is responsible for the decrease of QW conductivity with increasing the sheet electron concentration in the range of $n_s = (2{-}3) \cdot 10^{16}\,\text{m}^{-2}$ and $n_s > 5.5 \cdot 10^{16}\,\text{m}^{-2}$.

2. The enhancement of the mobility with increasing a QW width because of reduction of the intrasubband scattering rates by PO-phonon absorption (W_{11}^a, W_{22}^a) at $n_s = 5 \cdot 10^{15}\,\text{m}^{-2}$ is limited by the increase of the intersubband scattering of the first subband electrons (W_{12}^a and W_{13}^a), and at $n_s = 3 \cdot 10^{16}\,\text{m}^{-2}$, by the increase of the scattering of the second subband electrons (W_{23}^a). The competition of these scattering mechanisms explains the alternate changes of the mobility with a QW width.

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