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Large increase of electron mobility in a modulation-doped AlGaAs/GaAs/AlGaAs quantum well with an inserted thin AlAs barrier

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Abstract. The electron(polar optical (PO) phonon scattering mechanisms which determine the electron mobility in a $Al_{0.25}Ga_{0.75}As/GaAs/Al_{0.25}Ga_{0.75}As$ quantum well (QW) with an inserted thin AlAs barrier are considered. It is shown that the decrease of the second subband electron scattering by PO-phonon emission is responsible for the large increase of the mobility in the QW with the inserted barrier.

Introduction

There are many attempts to reduce electron(phonon scattering in modulation-doped quantum wells (QW) by confining polar optical (PO) phonons in a QW [1, 2]. It was shown that a thin barrier inserted into the QW reduces strongly electron scattering by confined phonons. But simultaneously the increase of electron scattering by interface phonons compensates this reduction. The competition of these scattering mechanisms determines the total electron scattering by 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 the increase of the mobility in a $Al_{0.25}Ga_{0.75}As/GaAs/Al_{0.25}Ga_{0.75}As$ QW with an inserted thin (1 nm) AlAs barrier are considered.

1. Confined electron–PO-phonon scattering rate and electron mobility

The transition frequencies $W_{ifv}^{a,e}$ of electrons, confined in a QW, from an initial state in subband i to any final state in subband f by emission (absorption) of v-mode PO-phonons are calculated by using the dielectric continuum model [3–6]. 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 electron–PO-phonon scattering rate is written as

$$W_{ifv}^{a,e} = \sum_{v} \int_{E_i}^{\infty} W_{ifv}^{a,e}(E) \frac{1 - f(E \pm \hbar\omega_v)}{1 - f(E)} \left[\int_{E_i}^{\infty} f(E) \mathrm{d}E \right]^{-1} \quad (1)$$

where E_i is the subband i bottom energy, $\hbar\omega_v$ is the phonon energy, and $f(E)$ is the electron Fermi–Dirac distribution function. The plus sign is for phonon absorption and the minus one is for phonon emission.

In this paper the estimation of a separate contribution of various type electron–PO-phonon scattering to electron mobility is done assuming the inverse mean frequency of electron transitions by PO-phonon absorption (emission) as a momentum relaxation time

$$\tau_{if} = \frac{1}{W_{if}}. \quad (2)$$

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 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

$$\mu_i = \frac{e}{m}\left[\sum_f \left(W_{if}^e + W_{if}^a\right)\right]^{-1} \tag{3}$$

and the total electron mobility in the QW is

$$\mu = \frac{1}{n_s}\sum_i \mu_i n_i \tag{4}$$

where n_s and n_i is 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 lower subbands (W_{11}^a, W_{12}^a, W_{22}^a). The enhancement takes place in the subbands with degenerate electron gas. This is largest in the lowest (first) electron subband (W_{11}^a), where electron gas is most degenerated (see Fig. 1(a)).

The scattering rates by phonon emission from the upper subband to the lower one (W_{31}^e, W_{32}^e, W_{21}^e) opposite decrease with electron gas degeneration in the lower subband.

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

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

3. The QW with an inserted barrier

A thin (1 nm) AlAs barrier inserted into the QW center changes the electron subband energies and divides PO phonon spectra into two independent branches located at both sides of the barrier [2].

The electron subband energies are divided into two pairs. The lower energy subband pair (first and second subbands) are occupied by electrons, and the upper subband occupation is negligible at $L < 30$ nm. The lower subband electron scattering by phonons determines the QW conductivity and electron mobility.

Figure 2(a) shows the dependence of scattering rates in the lower subbands of the QW with a barrier on the sheet electron concentration n_s. Because the phonon emission between

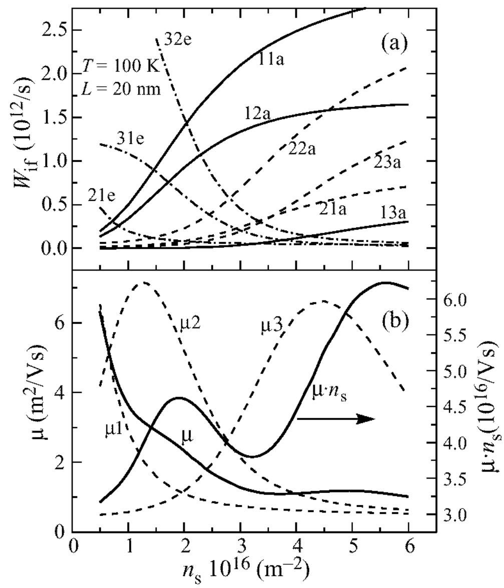

Fig. 1. The electron–PO-phonon scattering rates W_{if} with electron transitions from the initial state in subband i to the final one in subband f by phonon emission and absorption (labeled by ife and ifa, respectively) (a) and the electron mobilities in subbands $i = 1, 2, 3$ (labeled by μ_1, μ_2, μ_3),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

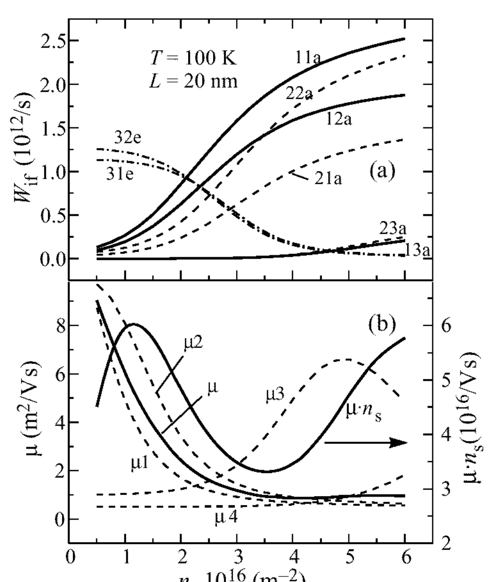

Fig. 2. The electron–PO-phonon scattering rates W_{if} (a) and the subband and total electron mobilities (b) as functions of sheet electron concentration n_s in the QW of width $L = 20$ nm. Notations are as in Fig. 1.

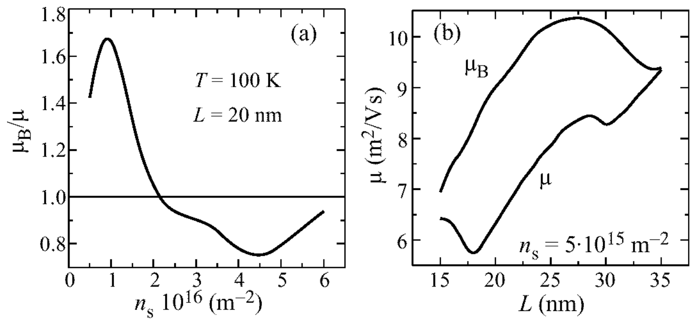

Fig. 3. The comparison of the mobilities in the QW with the inserted barrier, μ_B, and without the barrier, μ, as functions of sheet electron concentration n_s (a) and of QW width L (b).

the closely placed first and second subband levels is not permitted, the electron scattering with phonon absorption determines the mobility of first and second subband electrons. The scattering rates by phonon absorption (W_{11}^a, W_{22}^a, W_{12}^a, W_{21}^a) remain the predominant mechanism in a wide range of doping level ($5 \times 10^{15} < n_s < 6 \times 10^{16}\,\mathrm{m}^{-2}$).

It is seen from Figs. 1(a) and 2(a) that the W_{11}^a and W_{21}^e in the QW with an inserted barrier are less than these scattering rates in the QW without a barrier. The decrease of the W_{11}^a for the strong reduction of the scattering rate by the confined phonons when the barrier is inserted into the QW is responsible [3]. As a result, the first subband mobility is larger in the case when the barrier is inserted into the QW. For the enhancement of the total electron mobility in the QW with the inserted barrier, the decrease of the W_{21}^e and, consequently, the increase of the second subband mobility is responsible (see Fig. 2(b)).

Figure 3 shows the mobilities in the QW with the barrier and without it.

Conclusions

The electron–PO-phonon scattering mechanisms which are responsible for the dependence of electron mobility in the QW with and without barriers on the doping level are determined. It is shown that:

1. The increase of the scattering by PO-phonon absorption is responsible for the decrease of QW conductivity with increasing the sheet electron concentration.

2. The insertion of a thin AlAs barrier into the $Al_{0.25}Ga_{0.75}As/GaAs/Al_{0.25}Ga_{0.75}As$ QW center closes with each other the first and second subband levels and decreases the scattering rates of the second subband electrons by PO-phonon emission (W_{21}^e). As a result, the electron mobility in the QW with the inserted barrier exceeds that in the QW without the barrier at $n_s < 2 \times 10^{16}\,\mathrm{m}^{-2}$. At $n_s = 5 \times 10^{15}\,\mathrm{m}^{-2}$ the increase of the mobility in the QW with the barrier takes place in the interval of $15 < L < 35$ nm.

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