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Resonant phonon-assisted depopulation in type-I and type-II intersubband laser heterostructures

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Abstract. We show that LO phonon-assisted interband tunneling in type-II intersubband laser heterostructures is more efficient for the fast depopulation of the lower lasing states than the corresponding intersubband process in type-I double quantum wells (DQW). The main peak of the electron-phonon resonance in type-II DQW corresponds to electron transitions from the lowest electron-like subband to the top of the highest heavy-hole subband, which is strongly spin-split and displaced from the center of the Brillouin zone due to the heterostructure asymmetry. Phonon-assisted depopulation can be conveniently employed even when the lower lasing level is designed near the upper edge of the heterostructure leaky window, where direct interband tunneling depopulation becomes inefficient. This design is beneficial for the laser performance providing the highest value of the matrix element for intrawell optical lasing transition and simultaneously preventing thermal backfilling of the lower lasing states.

The InAs/GaSb/AlSb material system is very promising for the implementation of high-temperature mid-infrared intersubband lasers covering the 3-5 and 8-12 μm atmospheric windows. Comparing with InGaAs/InAlAs type-I heterostructures, the higher conduction band offset at InAs/AlSb interface allows an extension of the laser operation to shorter wavelengths, while the cross-gap alignment between InAs and GaSb contributes to the better blocking of the injected electrons in the upper lasing states. The lower lasing state depopulation, which is crucial for achieving the inverse population in intersubband lasers, in type-II heterostructures can be favourably accomplished by two efficient processes: the direct interband tunneling through the InAs/GaSb "leaky window" ($0<\varepsilon<\delta$) and LO-phonon assisted interband electron transition from the lower electron-like lasing subband $c1$ into the highest hole-like subband $hh1$; see Figure 1. In type-II lasers, the direct interband tunneling has always been considered as a basic depopulation mechanism, while the interband LO-phonon assisted process is habitually treated as an inefficient one due to a symmetry difference between the initial (electron-like) and final (hole-like) states involved in the transition. In our previous work [1] we have shown that the efficiency of the direct interband tunneling depopulation, being

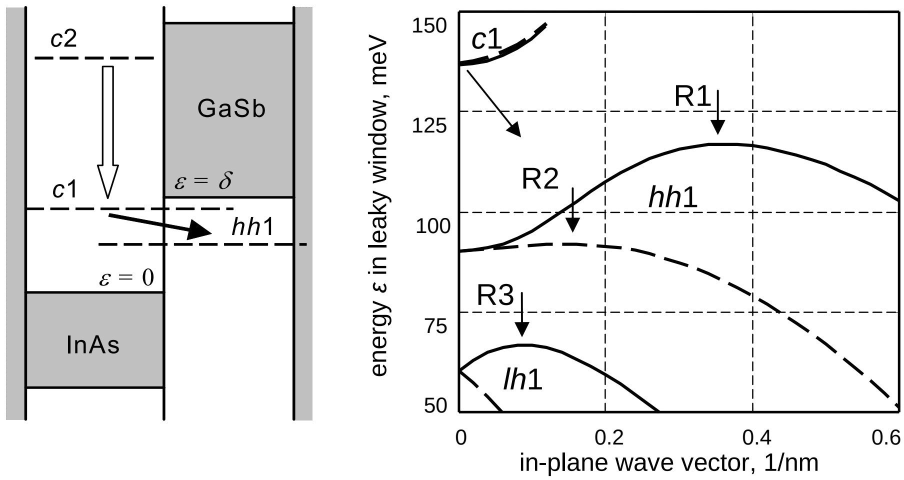

Figure 1. Left: schematic band diagram of an asymmetric InAs/GaSb DQW modeling an active region of intersubband type-II cascade laser. Black arrow depicts the interband LO-phonon assisted depopulation process. Right: subband splitting in the upper part of the leaky window δ. Short vertical arrows indicate the positions of the Van Hove singularities.

determined by a ratio $\varepsilon(\delta-\varepsilon)/E_{gInAs}E_{gGaSb}$, significantly decreases when the depopulated electron-like level *c*1 is located near the upper edge of the heterostructure leaky window $\varepsilon\sim\delta$. The latter configuration, however, is the most desirable from the standpoint of ensuring the highest oscillator strength for the lasing transition and preventing thermal backfilling of the lower lasing states.

In this paper, we analyze the process of the lower lasing state depopulation in type-II cascade laser heterostructures and show that the band mixing and the subband nonparabolicity effects inside the heterostructure leaky window essentially remove the symmetry constraint for interband phonon-assisted transition and can provide for a sufficiently strong overlap between electron and phonon states participating in the transition. Inherent asymmetry of type-II InAs/GaSb double quantum well (DQW) lifts the degeneracy of the hole-like subbands in the heterostructure leaky window and results in strong Van Hove singularities in the joint density of states. The peak value of the density of states at the top of the upper hole-like subband can be favourably combined with the maximum electron-phonon overlap, thus providing for the fast electron relaxation from the *c*1 into the *hh*1 subband. Subsequent tunneling from *hh*1 states into the InAs reservoir does not limit the depopulation rate since there is only one interface to penetrate in this tunneling process. The phonon-assisted depopulation can also be designed as a two-step process with the secondary resonant *hole* transition from deeper lying *lh*1 subband states or from an adjacent secondary GaSb QW, which is often used as an additional blocking layer for the electrons in the upper lasing subband.

Figure 1 illustrates the splitting of the hole-like subbands in the leaky window of a model isolated InAs/GaSb DQW with d_A= 9 nm and d_B = 5 nm. This "Rashba-type" splitting is inherent to any asymmetric DQW heterostructures and is especially strong in type-II heterostructures based on the narrow-gap InAs/GaSb material system [2]. Subband splitting displays the subband extremities from the Brillouin zone center and results in strong Van Hove singularities in the density of states, which can be used to engineer the phonon-assisted transitions of high efficiency. Electron states inside the

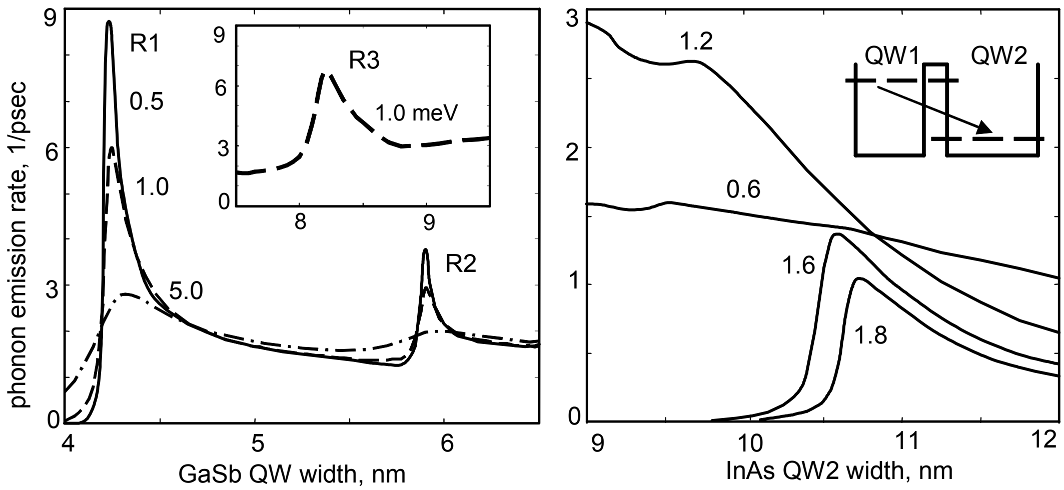

Figure 2. Comparison of the LO-phonon assisted depopulation rates in type-II InAs/GaSb DQW (left, curves are labeled with the level broadening in meV) and type-I InAs/AlSb/InAs DQW (right, curves are labeled with the width of AlSb barrier in nm, level broadening is 1 meV).

leaky window are quasibound with the width Γ determined by the interband tunneling, $\Gamma \propto \Gamma_{tun}$, which is about 1 meV in the upper part of the window [1]. Such level broadening can be accounted for in the Γ_{ph} rate calculations by including a Lorentzian lineshape function for the phonon emission transition. The phonon-assisted depopulation rate, Γ_{ph}, was calculated by assuming that final states for electron transitions are unoccupied, which is a rather good approximation for the uppermost states in the upper hole-like subband *hh*1. Since the LO-phonon energies are similar in both constituent materials, $\hbar\omega_{LO} \approx 30$meV, we can neglect the polar mode confinement and calculate the phonon emission rate within the 3D phonon approximation, that is assuming that the confined 2D electrons interact with dispersionless 3D bulk LO phonons. For a general discussion of phonon-assisted processes in nanostructures, see Ref. 3.

In Figure 2 we compare the LO-phonon spontaneous emission rates Γ_{ph} in type-II InAs/GaSb (left) and type-I InAs/AlSb/InAs (right) DQWs. For type-II DQW Γ_{ph} is shown as a function of the GaSb QW width d_B, with the InAs QW width kept constant at d_A = 9 nm. This value of d_A allows for the *c*1 states to be located near the upper edge of the leaky window δ. The increase of d_B in the range from 4 nm to 10 nm, while keeping the energy position of the initial electron-like subband *c*1 practically unchanged, makes it possible to scan the final states in the hole-like subbands E_f, here - the heavy-hole subband *hh*1 and the light-hole subband *lh*1, which thus move toward the upper part of the heterostructure leaky window. Type-II DQW clearly demonstrates three peaks in the LO-phonon emission rate, R1-R3, which are related to three consecutive resonances indicated in Figure 1. The first, most important resonance, R1, corresponds to the onset of spatially indirect (interwell) $c1 \rightarrow hh1$ phonon-assisted transition. R1 transition is indirect also in the momentum space since the top of the subband *hh*1 is noticeably displaced from the Brillouin zone center due to the subband spin splitting enhanced by the heavy-hole/light-hole mixing. Final momentum transfer in this resonance is important for the high phonon emission rate, because the interband transition can be engineered so that the peak of the density of states at the top of *hh*1 subband is complemented by the maximum value of the electron-phonon overlap integral $I(q)$; see Figure 3. This design explains the higher value of Γ_{ph} in R1 resonance comparing to the next resonance R2,

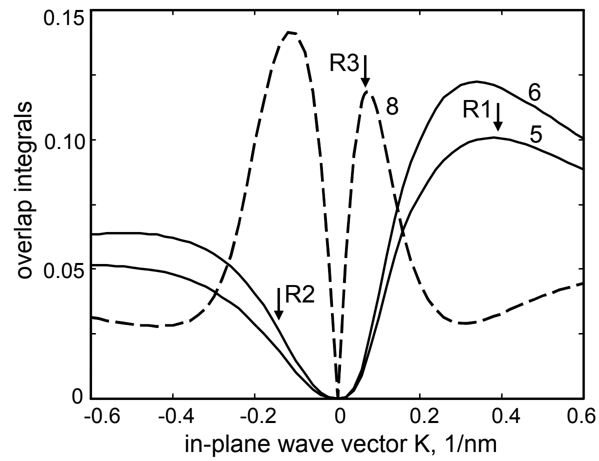

Figure 3. Electron-phonon overlap integrals $I(q)$ for $c1 \rightarrow hh1$ (solid lines) and $c1 \rightarrow lh1$ (dashed line) transitions vs. transferred (phonon) wave vector. Each curve is labeled with GaSb QW width d_B in nm and with a vertical arrow marking the position of the Van Hove singularity.

which is less pronounced due to the smaller electron-phonon overlap. With d_B increasing, R1 resonance becomes less efficient, firstly, because of the corresponding decrease of the final density of states for phonon-assisted transitions away from the top of the *hh*1 subband, and secondly, due to the suppression of the electron-phonon overlap integral $I(q)$ both at small and large momentum transfers. Finally, the increase of the phonon emission rate in the region R3 (see inset) corresponds to the onset of interwell electron transitions to the top states of *lh*1 subband, which are also displaced from the Brillouin zone center; see Figure 1. For type-I DQW (see Figure 2, right) the depopulation rate is shown as a function of the second InAs QW width d_{A2}, with the first InAs QW width d_{A1} = 9 nm. The decrease of d_{A2} from 12 nm to 9 nm reduces the separation between the initial and the final states for the phonon-assisted electron transitions and increases the rate of the spontaneous phonon emission. The cutoff of the phonon emission, which is typical for type-I DQW with sufficiently wide barrier layer d_b, corresponds to the subband separation below the optical phonon energy. For narrow barrier, d_b = 1.2 nm, the anticrossing gap dominates the separation and makes the emission possible in the whole range of d_{A2} values. Note, however, the overall remarkable decrease of the emission rate for the smaller barrier width, d_b = 0.6 nm, which is due to the increased subband separation under the anticrossing. It is readily seen also that the overall scale of the depopulation rate is in favor of the interband vs. intersubband depopulation.

In conclusion, we show that in type-II intersubband laser heterostructures the interband LO-phonon-assisted scattering can be used as an efficient complementary process for the fast depopulation of the lower lasing states.

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References

[1] Kisin M V, Stroscio M A, Luryi S and Belenky G 2001 Physica E **10** 576-586.
[2] Kisin M V, Dutta M and Stroscio M A 2002 in Advanced Semiconductor Heterostructures (World Scientific, Singapore, in press).
[3] Stroscio M A and Dutta M 2001 Phonons in Nanostructures (Cambridge University Press, Cambridge).