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Tailoring of optical phonon modes in nanoscale semiconductor structures: role of interface-optical phonons in quantum-well lasers

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Abstract

This paper discusses the concept of enhancing semiconductor laser performance through tailoring of scattering rates of confined polar-optical phonons. Studies of optically pumped intersubband scattering in coupled quantum-well lasers have demonstrated that interface-phonon-assisted transitions are important in such structures; furthermore, simple analytical expressions have been derived that indicate the importance of interface-phonon scattering in quantum-well lasers. These calculations reveal that the interface-phonon-assisted transitions are dominant for small quantum well dimensions of approximately 40 Å; such dimensions are typical of novel lasers including both the unipolar quantum cascade laser and the tunneling injection laser. Recent numerical calculations have confirmed these effects and have extended them to indicate how confined and interface phonons also affect critical laser properties such as optical gain. The application of confined phonon effects to intersubband lasers is one of the most important applications of confined-phonon physics to the present time. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Interface phonons; Quantum-well lasers; Phonon confinement; Phonon-assisted transitions

This paper presents theoretical results on the tailoring of polar-optical-phonon scattering [1,2] in quantum-well lasers through the control optical phonon amplitudes via the engineering of phonon modes [3,4] in such structures. Recently, optically pumped intersubband scattering in coupled quantum-well lasers have been examined [5–9] and it has been demonstrated that interface-phonon-assisted transitions are important in such structures; these findings represent one of the most important manifestations of phonon confinement effects discussed to date. As is now recognized, the proper

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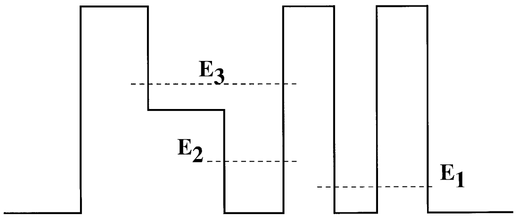

Fig. 1. Step quantum-well laser with E_1 and E_2 separated by the LO-phonon energy.

treatment of optical-phonon confinement in optical systems such as semiconductor lasers depends critically of the detailed energy spectrum of the phonon spectrum. The case of carrier transport is in contrast with that of semiconductor lasers since they have precisely defined bound states and phonon-assisted transitions between such states occur only if the phonon energy is well matched to the carrier transition energy. The calculations of Stroscio et al. [10,11] demonstrate the importance of considering the energy spectra in such devices and are relevant to a number of novel current injection semiconductor intersubband lasers [12,13,22]. One embodiment of such a laser structure is depicted in Fig. 1 where the energy levels E_2 and E_1 are separated by an energy equal to the optical-phonon energy. Phonon-assisted transitions between the levels with energies E_2 and E_1 depend strongly on the phonon energy involved in the transition. For the specific case of $Al_xGa_{1-x}As$-based structures such as that of Fig. 1, there are interface modes in the GaAs regions with energies close to the AlAs optical-phonon energy of 50 meV. Ref. [10] presents Fermi golden rule calculations comparing the longitudinal-optical (LO) phonon-assisted transition rates for a related structure. Specifically, Ref. [10] presented simple scaling relations for two of the dominant scattering processes: AlAs-like interface-phonon-assisted transitions where the phonon energy is in the range of 45–50 meV, and GaAs confined-phonon-assisted transitions where the phonon energy is close to 36 meV. These results reveal that the interface-phonon-assisted transitions are dominant for small quantum-well dimensions of approximately 40 Å or less. Such dimensions are typical of those used in the novel lasers of Refs. [12–14,22]; such novel lasers include both the unipolar quantum cascade laser and the tunnelling injection laser. Based on detailed and precise numerical computations, Ref. [11] demonstrated that the gain of such a semiconductor laser system depends critically on using the confined, interface and half-space phonons which result from phonon confinement. In a recent numerical calculation, J.-P. Sun et al. [15] have confirmed the importance of phonon confinement effects as predicted in Ref. [10] but Ref. [15] has not made a number of approximations made in Ref. [10]. Moreover, the results of Ref. [16] have provided a transfer-matrix technique for determining the interface phonon modes in multi-layer semiconductor heterostructures such as those considered in Refs. [12–14,22]. Kisin et al. [17] have demonstrated that energy spectra of confined phonons have a pronounced influence on intersubband optical gain in quantum-well lasers for the specific cases where selected phonon energies are resonant with electronic energy differences. Based on the results and concepts of Refs. [10,16,17], the influence of confined phonon effects on scattering rates have been considered for three-interface heterostructures [18] as well as for step quantum well structures [19] where phonon assisted intersubband transitions are critical to the operation of the laser.

To illustrate the role of phonon-assisted transitions in quantum-well lasers, we consider the simplified single-step quantum-well structure of Fig. 2 where the width of the inner well is taken to be 15 Å and that of the outer well is 420 Å; the depths of the inner and outer wells are taken to be 0.2 and 0.3 eV, respectively. Based on the Fermi golden rule, the LO-phonon-assisted transition rates between E_2 and E_1 for this structure are determined for two cases: a rate of $3.0\times10^{13}\ s^{-1}$ with a half width of 6 meV is obtained for the case when an antisymmetric interface (IF) optical phonon is emitted in the electron transition from E_2 to E_1; and a rate of $1.2\times10^{12}\ s^{-1}$ with a half width of 6 meV is obtained when a bulk GaAs LO phonon is emitted in the electron transition from E_2 to E_1. These results demonstrate that LO-phonon-assisted transition rates can be enhanced significantly when E_2-E_1 is equal to the energy of the interface optical phonon rather than the energy of a bulk

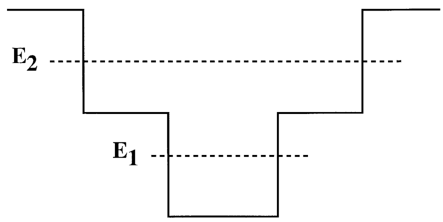

Fig. 2. Single-step quantum-well laser structures.

optical phonon; this result is consistent with the previously known condition that IF phonons may play a dominant role when the quantum well has a thickness of about 40 Å or less [10,16,17,19]. For these small sizes, the exponential decay of the interface modes with distance from the heterointerface is not the dominant effect and the scattering from interface modes is larger than that from the other phonon modes. The simplified single-step quantum-well structure of Fig. 2 is useful in gaining insights into the relative importance of interface-phonon-assisted and bulk-phonon-assisted transitions; however, the interface-phonon mode spectrum is significantly more complicated for complex heterostructures as illustrated in Fig. 3 which depicts the fifteen IF modes of a five-interface heterostructure. These more complicated phonon spectra are currently being employed to gain additional insights into the role of interface-phonon-assisted transitions in quantum-well lasers.

The influence of confined phonon effects is manifested in another important way in semiconductor lasers. Specifically, the optical gain of such a quantum-well semiconductor laser [20,21] depends on the integral of the phonon-broadened line shape function [17]; for the case of an $Al_{0.3}Ga_{0.7}As$/ GaAs/$Al_{0.3}Ga_{0.7}As$ double-heterostructure quantum-well laser having a well width of 60 Angstroms, a four-band Kane model and the confined phonon modes of the dielectric continuum model [2] predict gain curves that depend on the energy of the laser transition and the phonon mode spectrum as shown in Fig. 4. In Fig. 4 the dashed lines represent the gain when only the bulk GaAs LO phonon is taken into account and the solid line represents the case where the full spectrum of confined, interface,

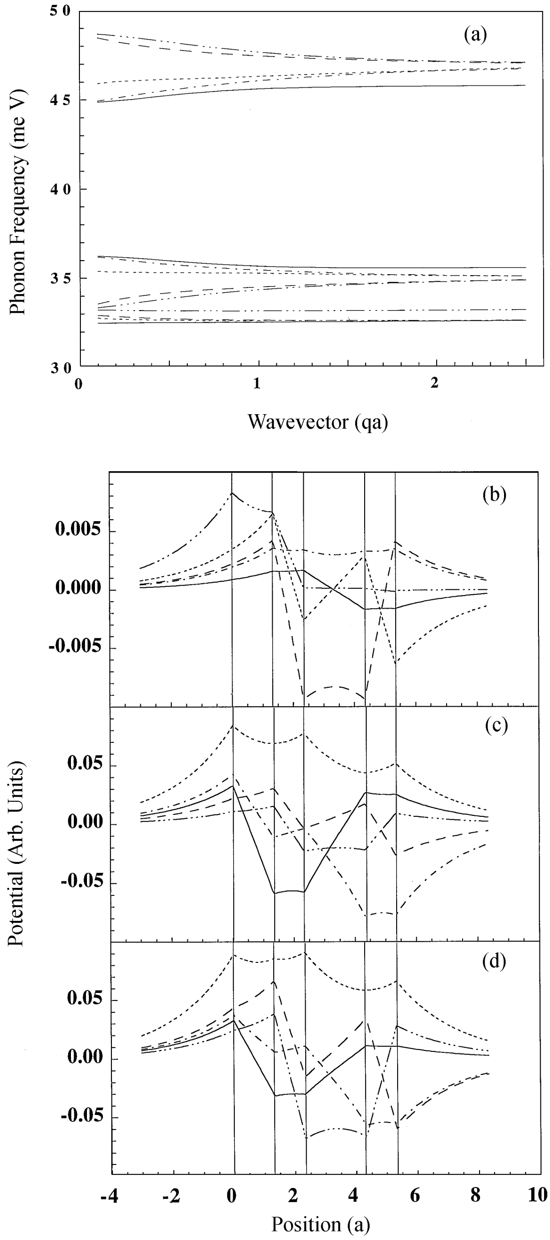

Fig. 3. (a) Phonon dispersion curves for interface modes in a five-interface $Al_yGa_{1-y}As$-GaAs-$Al_xGa_{1-x}As$-GaAs-$Al_xGa_{1-x}As$-GaAs heterostructure with $y = 0.25$ and $x = 0.6$. Electrostatic potentials versus distance for the same five-interface heterostructure are depicted for three cases: (b) lower GaAs-like modes, (c) upper GaAs-like modes, and (d) AlAs-like modes. The value of the wavevector, qa, is fixed at 0.5 and the unit for the position is a.

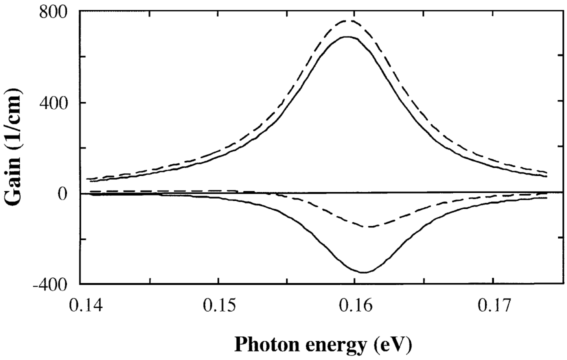

Fig. 4. Gain versus photon energy for quantum-well laser for two phonon models: dashed lines – bulk GaAs LO phonons; solid lines — full spectrum of confined, interface, and half-space phonon modes. The two curves exhibiting positive gain were calculated with an escape time of 0.4 ps and the two curves exhibiting maximum negative gain near 0.16 eV were calculated for an escape time of 0.6 ps.

and half-space phonon modes is taken into account. The escape time of the electron from the lower laser level is taken to have representative values of 0.4 ps and 0.6 ps; when the escape time is 0.4 ps, both gain curves are positive over the entire range of energy depicted in Fig. 4, but for the case where the escape time is 0.6 ps, the gain curves are negative over most of the depicted energy range. The importance of phonon-confinement effects is thus reflected in the optical gain.

The role of optical-phonon confinement in semiconductor nanostructures motivates the application of optical-phonon confinement in semiconductor nanostructures. The current excitement in this field has been caused in part by the successful room-temperature infrared operation of intersubband lasers by the team of Ref. [14]. The application of confined phonon effects to intersubband lasers is easily one of the most important application of confined phonons in semiconductor devices.

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