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Calculations of the inter-subband scattering rates of electrons in GaAs/AlGaAs quantum wells

H.C. Lee[a], K.W. Sun[b,*]

[a]Department of Electronic Engineering and Institute of Electronics, National Chiao Tung University, Hsinchu, Taiwan, ROC

[b]Department of Physics, National Dong Hwa University, 1 Da Hseuh Road Sec 2, Hualien 974, Taiwan, ROC

Abstract

In this presentation, we report the calculated results on hot electron relaxation through inter- and intra-subband scatterings with LO phonons in quantum well structures. The scattering rates were calculated for electrons excited both in the gamma valley and L valleys. The types of optical phonons adapted in our model are determined based on the dielectric continuum model. We have also studied the dependence of the scatterings on the structure parameters of the quantum well.

Keywords: Inter-subband; Quantum wells; Phonons

1. Introduction

In the last two decades the realization of low-dimensional structures, like quantum wells, superlattices, and quantum wires, opened a new exciting chapter of semiconductor physics and technology. The electronic transitions of interest in quantum wells can be classified as inter- and intra-subband scattering when many bands are present in the wells. One of the most important sources of scattering that determine electron transitions in low-dimensional semiconductor structures is phonons. The layered structure of low-dimensional systems has fundamental consequences on their vibrational properties, which are strongly modified with respect to the bulk case. Most of the studies which have appeared in the literature are based on 'macroscopic models' which assume the sample to be a continuum [1,2].

In Mori's work [2] two sets of modes are found: (i) confined modes in the GaAs-like frequency range, whose displacements are represented by sine and cosine functions; (ii) interface (IF) modes, whose potential and frequency strongly dependent on the in-plane phonon wave vector. These modes have been observed experimentally by Raman spectroscopy [3,4]. More Recently, the structure dependence of the electron relaxation via intra-subband scatterings in GaAs/AlGaAs quantum wells has been studied both experimentally and theoretically in Refs. [5,6]. In this report, we investigate the inter-subband scattering and the dependence of the scattering rates on the structure parameters, such as the well width, for electrons excited in gamma and L valleys.

2. Theoretical model

We calculated the electron–LO phonon inter- and intra-subband scattering rate as a function of well width and electron excess kinetic energy in quantum wells using the dielectric continuum model (DCM). Base on DCM, there are six types of optical phonon modes in a dielectric slab. However, due to selection rules, only the confined LO mode, the half-space LO mode and symmetric IF modes were taken into consideration in our calculations.

The confined phonons propagate in the well, and the component of the phonon wave vector along the layer growth direction (z direction) is quantized. The half-space phonons, whose z component of the phonon wave vector is not restricted; propagate in the barrier. Symmetric IF phonons propagate along the IF, and the in-plane atomic displacement is symmetric with respect to the center of the well. Symmetric IF mode can be further divided into the symmetric plus branch (noted as $S+$ in the text), and the symmetric minus branch ($S-$). These two phonon branches also have different dispersion characteristics [6].

The electron–optical phonon interaction Hamiltonians for all modes in a dielectric slab are taken from the work of

* Corresponding author. Tel.: +886-3-8662500; fax: +886-3-8662303. *E-mail address:* kwsun@mail.ndhu.edu.tw (K.W. Sun).

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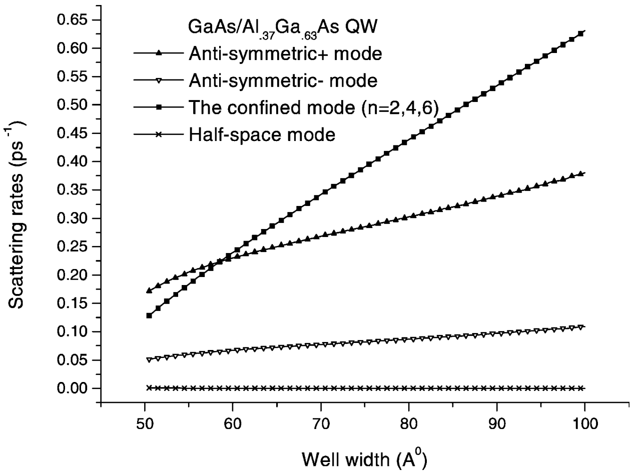

Fig. 1. Calculated electron–LO phonon inter-subband scattering rates as a function of well width.

Ando and Mori [2]. The quantum well structure that we used in our calculation has an $Al_{0.37}Ga_{0.63}As$ barrier with width of 40 nm. The inter-subband electron–optical phonon scattering rates between different subbands were calculated using the Fermi's golden rule. The scattering rates are obtained by integrating over all possible states using the two-dimensional density of state function and the inter-subband transitions are restricted by energy and momentum conservations. The dispersion relationships of the $S+$ and the $S-$ interface modes are given in earlier report in Ref. [6].

Structure effects on inter-subband transitions with phonons in GaAs/AlGaAs quantum wells were studied. In order to compare the calculations with experimental results in Ref. [7], only two confined states are considered in the calculations of the dependence of scattering rates on well widths.

3. Results and discussion

In Fig. 1 we have plotted the electron–LO phonon inter-subband scattering rates of different phonon modes in a $GaAs/Al_{0.37}Ga_{0.63}As$ quantum well as a function of well width. Note that there will be more than two confined states in the wells with the well width approaching 10 nm. Scattering between e2 and e1 subband is affected principally by the IF and confined phonon mode with odd potential symmetry.

We discover that, in narrow quantum well structures, the inter-subband scattering rates of the confined mode and anti-symmetric + mode are comparable. This indicates that the IF phonon mode does play a very important role in phonon-assisted inter-subband transitions for narrow quantum wells. The calculated scattering rates of the both confined mode and anti-symmetric + mode, with decreasing tendency for smaller well width, correspond to LO phonon-assisted inter-subband scattering, which requires larger wave vectors with increasing subband splitting. However, with increasing well width, the confined phonon mode has become the dominant mode that assists the inter-subband transition. The scattering rate for the confined mode exceeds the rate of the $A+$ mode when the well width is larger than about 5.7 nm. The calculated results are in good agreement with the earlier experimental results in wide GaAs/AlGaAs quantum wells as reported in Ref. [7].

We have also calculated scattering rates of e3–e2 and e3–e1 transitions at the fixed well width of 10 nm in which there are three confined states at this well width. The results are plotted as a function of electron excess energy as shown in Fig. 2. We discover that the confined phonon mode does show higher scattering rates for transitions among higher subbands. Most importantly, we found that the e3–e1 transition is faster than e2–e1

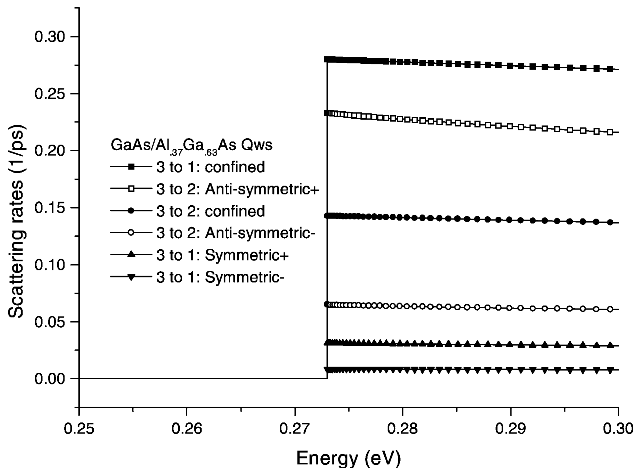

Fig. 2. Calculated electron–LO phonon scattering rates as a function of electrons' excess kinetic energy among higher subbands.

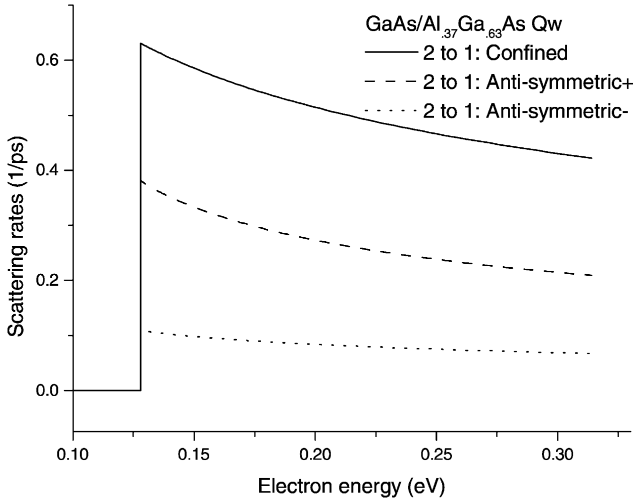

Fig. 3. Calculated electron–LO phonon scattering rates of e2–e1 transition as a function of electrons' excess kinetic.

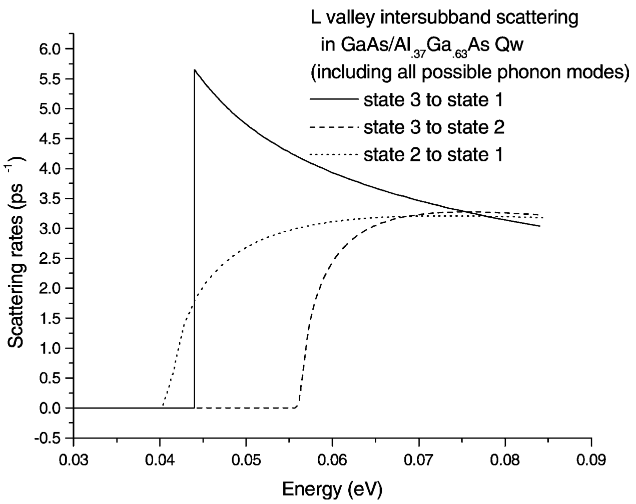

Fig. 4. Calculated inter-subband scattering rates of electrons in L valley as a function of electron excess energy.

transition, both assisted mostly by confined optical phonon.

In Fig. 3, we show the scattering rates of e2–e1 transition as a function of electron excess energy in the same well. Again, the confined phonon mode gives the highest scattering rate among the phonon modes that we have studied.

If the electrons were initially created with sufficient excess kinetic, they can transfer to the L valleys. Those electrons scattered to the L valleys will also lose their energy by interacting with optical phonons. We have also calculated the inter-subband scattering rates of electrons confined in the L valleys with all possible phonon modes. The results are shown in Fig. 4. There are three confined states in the L valleys for the given quantum well structures in our calculations.

Due to the larger effective mass of electrons in the L valleys and smaller subband energy separation, the scattering rates in L valleys are faster than those in the gamma valley.

4. Conclusion

In conclusion, we have studied the inter-subband scattering of electrons in $GaAs/Al_{0.37}Ga_{0.63}As$ quantum well. In our calculations, the types of phonons that interact with electrons in the wells are determined based on the DCM. In contrast to the earlier results in narrower quantum wells, we find that the inter- and intra-subband transitions are both dominated by the confined LO phonons for wide GaAs/AlGaAs well and the inter-subband scattering rates are faster for electron confined in L valleys than those in the gamma valley. Our results are in good agreement with recent experimental results.

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