Structure effects on inter- and intra-band scattering of electrons in $GaAs/Al_xGa_{1-x}As$ and strained $In_xGa_{1-x}As/GaAs$ quantum wells

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ABSTRACT

Based on the dielectric continuum model, we have studied the dependence of electron-optical phonon scattering rates in $GaAs/Al_xGa_{1-x}As$ quantum wells with different structure parameters. It was found that the dependence of scattering rates of symmetric interface mode on Al composition in the barrier was stronger than that of the confined mode. The average phonon energy emitted by hot electrons in $GaAs/Al_xGa_{1-x}As$ quantum wells with various Al composition was estimated and the calculated value agrees with the experimental results qualitatively. For the dependence on the well width, scattering rates of the S+ mode dropped considerably as the well width is increased. The hot electron-neutral acceptor luminescence spectrum of the strained $In_xGa_{1-x}As/GaAs$ quantum well sample shows an oscillation period of about 22 meV which indicates that the hot electrons relaxed mostly through emissions of the InAs confined phonons.

Keywords: quantum wells, optical phonon, inter-subband scattering, hot electron, neutral acceptor

1. INTRODUCTION

In the past, electron-phonon scattering rates in a quantum well structure were typically calculated using the bulk phonon model or the bulk-like phonon model. The bulk-like phonon model is that the optical phonon modes in the heterostructures were assumed the same as those of the bulk material while electron's wave function was treated with the quantum confined effect. More recently, the dielectric continuum model [1–4] (DCM) and Huang-Zhu model [5] were developed and found to be much better than the bulk and the bulk-like phonon models. The corresponding fundamental types of phonon modes [1, 4, 5] and electron-phonon Hamiltonian [2, 3, 5] in the heterostructures have become an interesting subject.

More recently, hot-electron neutral-acceptor luminescence [6] was also developed to study electron- optical phonon interaction due to its better spectral resolution and lower carrier excitation than that excited by an ultrafast laser. The experimental method was used to determine optical-phonon energy in GaAs/AlAs multiple quantum wells with different well widths and barrier thicknesses by Sapega [7–8]. Sun *et al.* have also studied [9] optical-phonon energy in $GaAs/Al_xGa_{1-x}As$ quantum wells with various Al compositions. Up to now, to our knowledge, there has not been any report on the calculations of the dependence of electron-optical phonon interaction on the Al composition. The purpose of this work is to calculate electron-optical phonon scattering rates in $GaAs/Al_xGa_{1-x}As$ quantum wells with various Al composition in the barrier based on the DCM in a quantum well structure. The calculations were compared with earlier experimental results.

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2. THEORY

2.1. Phonon Energy in GaAs/$Al_xGa_{1-x}As$ Quantum Wells

Base on DCM, there are six types of optical-phonon modes [3] in a dielectric slab. However, due to selection rules for intrasubband scattering only the confined LO mode, the half-space LO mode, symmetric interface modes were taken into consideration in our calculations.

The energy of the S+ and the S− interface phonon modes is given by the solution of

$$\varepsilon_1(\omega_{S\pm})\tanh(q_{\|}L/2) + \varepsilon_2(\omega_{S\pm}) = 0,$$

where the subscripts 1 and 2 denote GaAs and $Al_xGa_{1-x}As$, respectively, L is the well width, and $q_{\|}$ is the in-plane phonon wave vector. The lattice dielectric function is given by $\varepsilon_n(\omega_{S\pm}) = \kappa_{\infty n}(\omega_{S\pm}^2 - \langle\omega_{Ln}\rangle^2)/(\omega_{S\pm}^2 - \langle\omega_{Tn}\rangle^2)$, where $\kappa_{\infty n}$ is the high-frequency relative permittivity of the n_{th} layer. In our calculations, all parameters of the $Al_xGa_{1-x}As$ alloy are taken from the work of Adachi [10]. In Fig. 1 we show the dependence of the phonon energy of the S+ mode and the S− mode on the Al composition in the barrier for minimum $q_{\|\min}$ and maximum $q_{\|\max}$ in-plane phonon wave vectors with a well width of 5 nm.

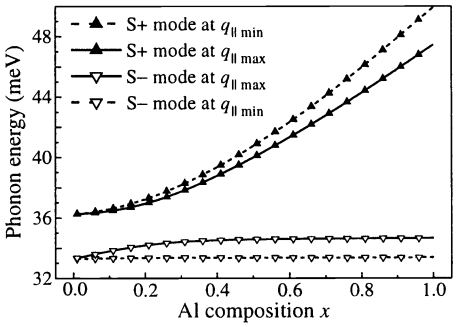

Figure 1: The dependence of the phonon energy of the S+ mode and S− mode on the Al composition at $q_{\|\min}$ and $q_{\|\max}$.

2.2. Electron-Optical Phonon Scattering Rates with and without Dynamical Screening

Electron-optical phonon interaction Hamiltonians for all modes in a dielectric slab are taken from the work of Ando *et al.* [3]. With the assumed average phonon energy in $Al_xGa_{1-x}As$ alloy shown earlier, intrasubband electron-optical phonon scattering rates in the lowest subband can be calculated using Fermi's golden rule. The scattering rates are obtained by integrating over all possible states using the two-dimensional density of state function with states restricted by energy and momentum conservation.

Dynamical screening in electron-phonon interaction is treated by random phase approximation, and the two-dimensional longitudinal dielectric function of plasma is given by

$$\varepsilon(q,\omega) = 1 - V_q^v \Pi_0(q,\omega)$$

where $V_q^v = (e^2)/(2\varepsilon_0\kappa_{\infty n}q)$ is the two-dimensional Fourier transform of the Coulomb interaction, and

$$\Pi_0(q,\omega) = -\frac{n_{2D}}{E_F}\frac{k_F}{q}\left[\frac{q}{k_F} - \left(a_+^2 - 1\right)^{1/2} + \left(a_-^2 - 1\right)^{1/2}\right]$$

is the zero-temperature polarizability function, where n_{2D} is the sheet charge density, k_F is Fermi wave vector, E_F is Fermi energy, and $a_\pm = (\omega + i\gamma)/(qv_F) \pm (q)/(2k_F)$, where ω is the phonon energy, damping coefficient $\gamma = (0.2\text{–}0.3)\omega$, and v_F is the Fermi velocity.

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3. RESULTS AND DISCUSSION

In Fig. 2 we show the calculated dependence of electron-optical phonon scattering rates on Al composition for various types of phonon modes in a GaAs/$Al_xGa_{1-x}As$ quantum well with a well width of 5 nm and a lattice temperature of 15 K. In Fig. 2 we also find that the screening effect for the S+ mode and the S− mode is not significant.

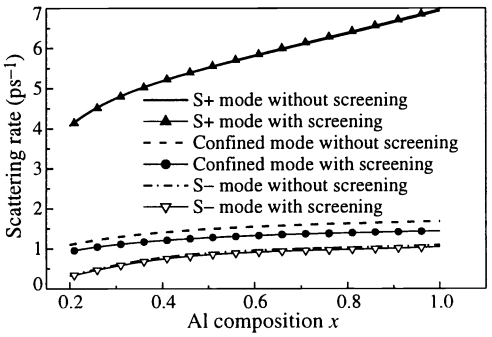

Figure 2: The dependence of the electron–phonon scattering rate of the S+ mode, the confined mode, and the S− mode on the Al composition. The well width is 5 nm, the lattice temperature is 15 K, and the amount of the excess kinetic energy of the electron is 50 meV.

Comparing to the S+ and the S− modes, the scattering rate of the confined phonon mode does not change very much with the Al composition in the range that we have investigated. The influence of screening for the confined mode is stronger than that of the S+ and the S− interface modes.

For the 5 nm well the electron wave function does not penetrate deeply into the barriers, therefore, the half-space mode's contribution to the scattering rate is insignificant comparing to the other three types of phonon modes and will not be considered here.

The calculated results were compared with experimental results [9] performed by hot electron neutral-acceptor luminescence for GaAs/$Al_xGa_{1-x}As$ quantum wells with various Al compositions. The calculated effective phonon energy (ω_{eff}) is given by the following equation.

$$\omega_{\text{eff}} = \frac{W_{\text{S+}}\omega_{\text{S+}} + W_{\text{S-}}\omega_{\text{S-}} + W_{\text{C}}\omega_{\text{C}}}{W_{\text{S+}} + W_{\text{S-}} + W_{\text{C}}}$$

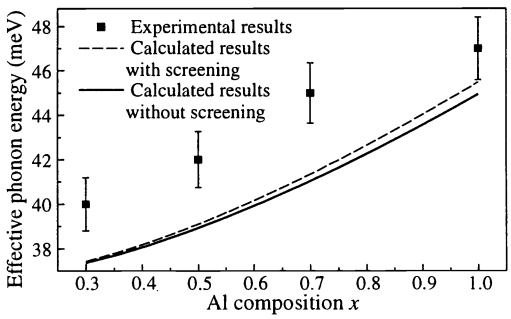

Figure 3: The comparison of experimental results and calculated results for the dependence of the effective phonon energy on the Al composition. The well width is 5 nm, the lattice temperature is 15 K, and the amount of the excess kinetic energy of the electron is 180 meV.

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where the W_{S+}, W_{S-} and W_C are the scattering rates of the interface and confined modes.

In Fig. 3 we show the dependence of the effective phonon energy on the Al composition based on both the experimental result [9] and our calculations. The minor difference between the measured result and the calculated result on the effective phonon energy is attributed to the assumptions that we made in the calculations of the average phonon energy in $Al_xGa_{1-x}As$ alloy, which probably simplified the complexity in the ternary compound.

In Fig. 4 we show the dependence of scattering rates on the well width for various types of phonon modes in $GaAs/Al_xGa_{1-x}As$ quantum wells with an Al composition $x = 0.3$. Other parameters are the same as in previous calculations. There is a crossover point of the scattering rate for the confined mode and the S+ mode at a well width of 10 nm and an Al composition of 0.3. So the confined mode is the major relaxation channel for hot electrons in wide quantum wells. Although the total scattering rate only varies slightly with the well width, there still can be a strong dependence of the average electron's energy-loss rate on the well width when the phonon energy of the corresponding modes is considered.

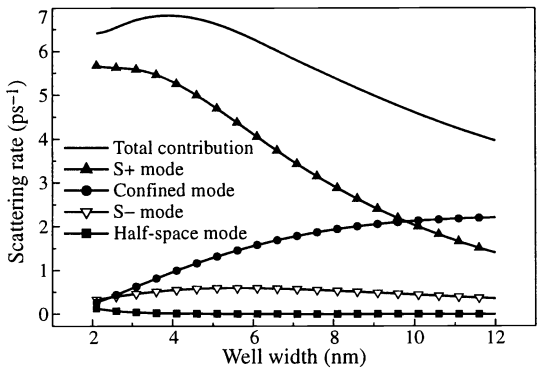

Figure 4: The dependence of the electron-optical phonon scattering rate of the S+ mode, the confined mode, the S− mode, the half-space mode, and the total rate contributed by all types of phonon modes on the well width. The Al composition is 0.3, the lattice temperature is 15 K, and the amount of the excess kinetic energy of the electron is 50 meV.

However, experimental wise, it is rather difficult to obtain decent hot electron luminescence spectra due to the deterioration of the AlAs morphology when wider wells and thick barriers were grown in the structures. Therefore, we turned to study the electron-optical phonon interactions in moderate wide $In_xGa_{1-x}As/GaAs$ strained quantum wells in order to determine the dominant LO phonon mode emitted by the hot electrons. The quantum well sample consisted of five layers of strained 10 nm $In_{0.3}Ga_{0.7}As$ wells with GaAs barrier of 30 nm prepared on GaAs substrate. The central regions of 2 nm of the $In_{0.15}Ga_{0.85}As$ wells were doped with Be to 10^{18} cm^{-3} in order to study its hot electron-neutral acceptor luminescence.

The energy difference between the peaks in the spectrum is about 22 meV and is close to the InAs confined phonon mode in the wells. Keep in mind that the GaAs-like phonon energy is close to 37 meV and the GaAs-like phonon mode was very unlikely the type of phonon emitted by the hot electrons excited in the wells. In comparing to the experimental results in the narrower GaAs/AlGaAs QWs, the phonon mode emitted by the hot electrons in the moderate wide QWs is now dominated by the confined phonon mode in the wells. The experimental results were also in good agreement with calculations qualitatively.

ACKNOWLEDGMENTS

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