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Investigation of electron–optical phonon interactions in moderate wide $In_xGa_{1-x}As/GaAs$ strained quantum wells

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Abstract

In this presentation, we have calculated the electron–optical phonon scattering rate of GaAs/AlAs quantum wells and average electron energy loss rate as a function of well width of the $GaAs/Al_xGa_{1-x}As$ quantum wells. We have also studied the Raman and hot electron–neutral acceptor luminescence in moderate wide $In_xGa_{1-x}As/GaAs$ strained quantum wells (with 10 nm in well width and 30 nm in barrier width) to determine the dominant phonon mode emitted by the hot electrons in the wells at 15 K. The hot electron–neutral acceptor luminescence spectrum of the strained 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: Photoluminescence; Strained quantum wells; Optical phonon

1. Introduction

It is well known that the main mechanism of scattering of hot electrons in bulk GaAs and GaAs/AlGaAs quantum wells (QWs) is inelastic scattering by optical phonons at low excitation densities. The relaxation of hot electrons through optical phonon emission in bulk GaAs [1–3] and heterostructures [4–6] has been extensively studied using the hot electron–neutral acceptor technique. Sapega et al. [7] has demonstrated that, for GaAs/AlAs quantum wells with large barrier widths, the energy relaxation mechanism for hot electrons is dominated by the AlAs interface phonons. For smaller barriers, emission via GaAs phonon is more important. More recently, Sun et al. [8,9] have shown that the relaxation of hot electrons in the $GaAs/Al_xGa_{1-x}As$ quantum wells was dominated by the GaAs LO phonon emission for small x, but by AlAs-like LO phonons for larger Al composition.

All the experimental and theoretical [10] evidence have indicated that the hot electrons relaxed mostly through AlAs-like interface phonon emissions for narrow quantum wells (about 5 nm in well width and 15 nm in barrier width). In this presented work, we have calculated the electron–LO phonon scattering rate in GaAs/AlAs quantum wells with fixed well widths of 15 nm and barrier widths of 30 nm. We also calculated the

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average electron energy loss rate as a function of well width in GaAs/$Al_{0.3}Ga_{0.7}As$ QWs. In contrast to the previous experimental results in narrower wells [7–9], the calculations show that, in wider wells, the most important scattering event is the electrons scattered by GaAs confined phonons. 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.

2. Calculations based on the dielectric continuum theory

The electron–optical phonon scattering rate was calculated via the Fermi's golden rule for types of phonon modes found in the dielectric continuum model: interface modes such as symmetric plus (S+) phonon mode, symmetric minus (S−) phonon mode and confined LO phonon mode. We first calculated the electron–LO phonon scattering rate in the GaAs/AlAs QWs with well width of 15 nm and barrier width of 30 nm. Details of the calculation will be published elsewhere [11]. Here we only show the final results. Fig. 1 gives the calculated electron–LO phonon scattering rates for interface S+, interface S− and confined LO phonon modes. We discovered that, in contrast to the previous experimental results in narrower wells, the GaAs confined phonons now have the highest scattering rate among three phonon modes.

We then calculated the average electron energy loss rate as a function of well width for GaAs/$Al_{0.3}Ga_{0.7}As$ quantum wells, assuming a carrier temperature of 600 K and lattice temperature of 8 K. The hot phonon effect has also been taken into account in the model. The calculated results

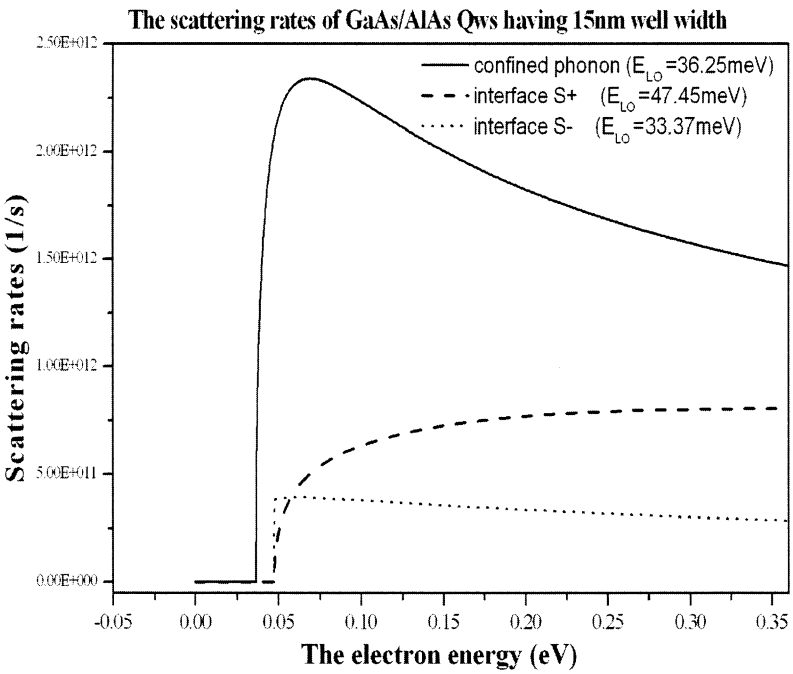

Fig. 1. The calculated scattering rates of the S+ interface phonon mode, S−interface mode, and confined phonon mode in a 15 nm GaAs/AlAs QW.

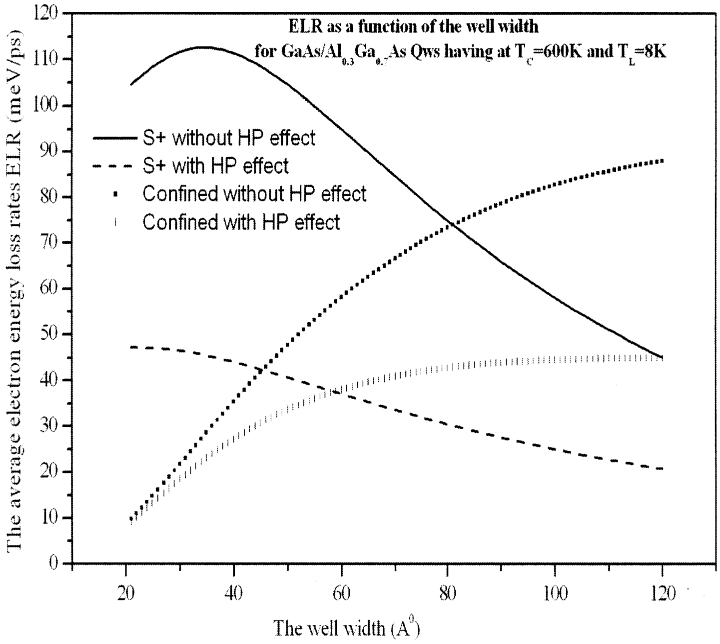

Fig. 2. The calculated average electron energy loss rates of the S+ interface phonon mode, S−interface mode, and confined phonon mode as a function of well width with and without hot phonon effect in $GaAs/Al_{0.3}Ga_{0.7}As$.

are shown in Fig. 2. Again, for well width larger than 8 nm, the electron energy loss rate is dominant by confined phonon in the well. When hot phonon effect was considered, this crossover occurred at well width of about 6 nm.

3. Experimental techniques

For the excitation of hot electron–neutral acceptor luminescence, a dye laser pumped by an Ar^+ laser was used. The dye laser was operated at appropriate photon energies to excite electrons with excess kinetic energy below GaAs barrier. About 30 mW of the laser power was directed on the samples, which were kept in a closed-cycle refrigerator at 15 K. The spectra were recorded with a combination of a SPEX 0.6 m triplemate spectrometer equipped with a liquid nitrogen cooled CCD detector.

For the Raman experiments, an Ar ion laser operated at 514.5 nm was used as the excitation source. About 150 mW of the laser was directed onto the samples, which were also kept in the refrigerator at 15 K. Raman spectra were obtained in back-scattering geometry and the scattering light was collected by a camera lens and pass through a notch filter before entering the spectrometer. The Raman spectra were analyzed with the same spectrometer and detector in the hot luminescence experiments.

Several samples grown by molecular-beam epitaxy were used in the Raman and luminescence study: a 1 μm thick epi-layer of $In_{0.5}Al_{0.5}As$ grown on a lattice matched InP substrate, an one μm thick epi-layer of $In_{0.5}Ga_{0.5}As$ also grown on a lattice matched InP substrate, QWs consisted of five layers of strained 10 nm $In_{0.15}Ga_{0.85}As$ wells with GaAs barrier of 30 nm grown on a GaAs substrate and QWs also 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.

4. Results and discussion

Raman scattering has been proven as a versatile and efficient tool for probing long-wavelength and short-wavelength lattice dynamics of ternary alloys. In these reports, we first use Raman scattering measurements to identify phonon modes in those samples. In Fig. 3, we have shown the Raman spectra of the two lattice matched samples. These Raman spectra show two-mode behavior as in the $Al_xGa_{1-x}As$ alloys [8,9]. Note that the GaAs-like peak found in the $In_{0.5}Al_{0.5}As$ sample is originated from the GaAs cap layer on the sample. However, in the strained $In_xGa_{1-x}As/GaAs$ QW sample, only the bulk GaAs phonon Raman peak was found in the spectrum (as shown in Fig. 4). In Fig. 4, we have also placed the Raman spectrum of the bulk GaAs sample for comparison.

Even though phonon modes in the strained QW sample could not be identified via Raman scattering measurements as in the GaAs/AlGaAs QWs, however, the phonon emitted by hot electrons still can be resolved by using hot electron–neutral acceptor luminescence technique. In Fig. 5, we have shown the hot electron–neutral acceptor luminescence spectrum of the $In_{0.15}Ga_{0.85}As/GaAs$ quantum well sample. The inset in the figure shows the schematics of the hot electron–neutral acceptor luminescence technique. The principles of this technique were given in Ref. [1]. The first peak in the spectrum was the so-called "unrelaxed peak" which corresponds to recombination of electrons, from the state at which they were created, with a neutral acceptor. The peaks other than the "unrelaxed peak" represents electrons recombining with neutral acceptors after emitting one LO phonon. The width of the peaks is determined by the electron energy distribution at the point of generation, which is related to heavy hole subband warping, as well as the energy distribution of acceptors, the final state of recombination for the hot luminescence process.

The photoexcited carrier densities are determined from the laser spot size on the sample and the absorption coefficient of the QW samples at the excitation wavelength. The power density of the laser used for the excitation was about $10\,W\,cm^{-2}$, which resulted in a 2D carrier density

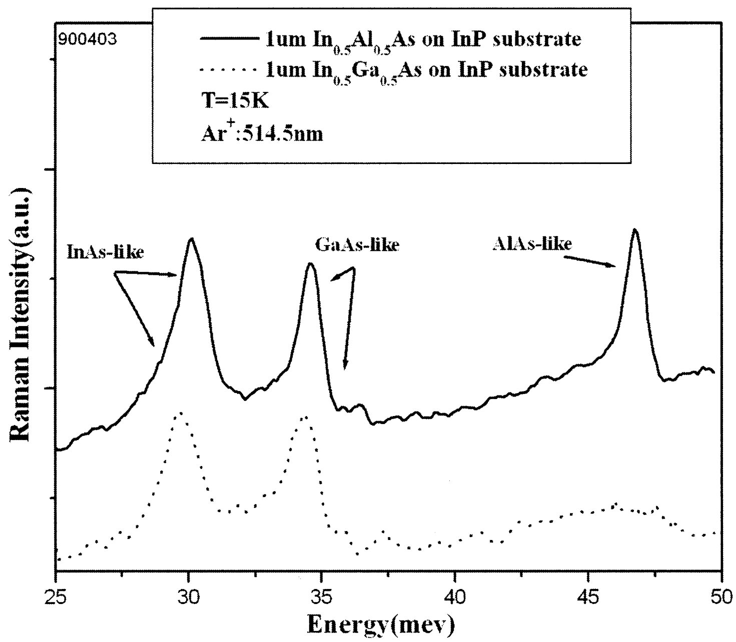

Fig. 3. Raman spectra of the $In_{0.5}Al_{0.5}As/InP$ and $In_{0.5}Ga_{0.5}As/InP$ lattice matched samples.

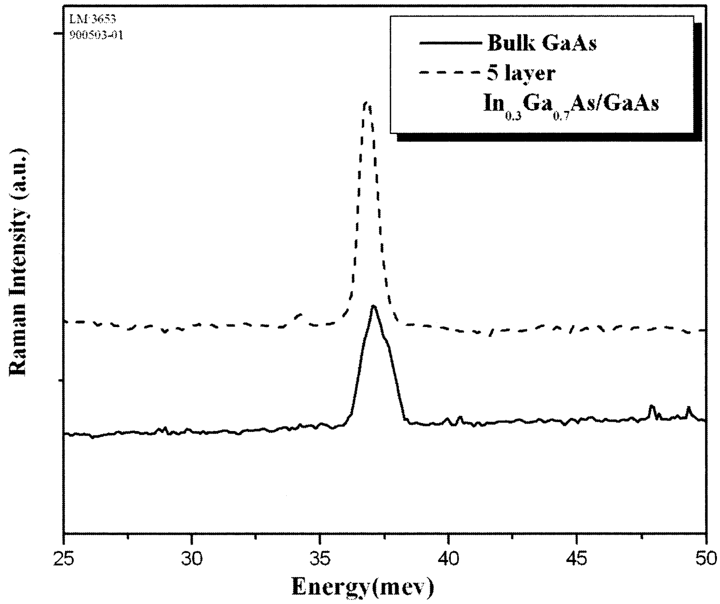

Fig. 4. Raman spectra of the $In_{0.15}Ga_{0.85}As$/GaA strained QW sample. The Raman spectrum of the bulk GaAs sample was also placed in the figure for comparison.

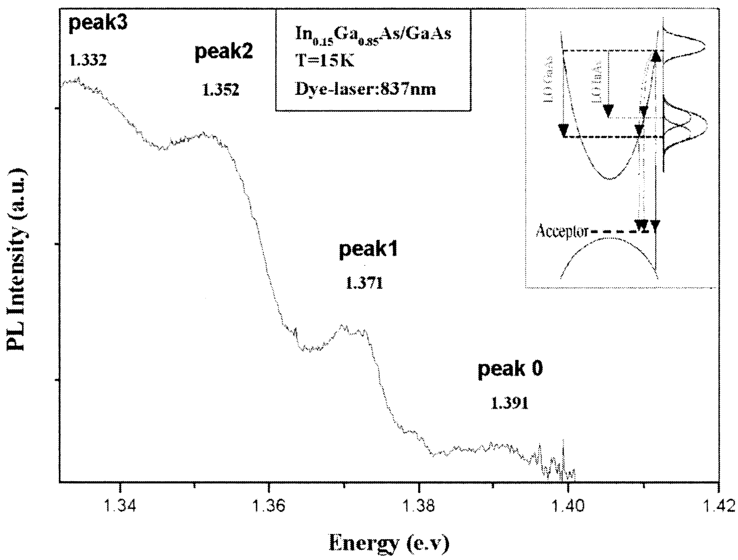

Fig. 5. The hot electron–neutral acceptor luminescence spectrum of the $In_{0.15}Ga_{0.85}As$/GaA strained QW sample with well widths of 10 nm and barrier width of 30 nm. The inset shows the schematics of this technique. The spectrum shows an oscillation period of 22 meV.

less than $10^9\,cm^{-2}$. Our photoexcited carrier densities are low enough so that the main mechanism of energy relaxation in the sample studied is the emission of optical phonons and the phonon–plasmon coupling can be ignored. In order to determine the energy separation more accurately, we first subtract the background (which was originated from the band-to-band recombination) from the spectra and the energy spectra of the remaining peaks were then fitted by Gaussian distributions. The energy difference between the peaks determined from the above method 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. A thorough calculation of the interaction strength between electrons and barrier phonons, confined phonons, and interface phonons in the $In_xGa_{1-x}As/GaAs$ strained QW structures is currently under investigation.

5. Conclusion

In conclusion, our calculations have shown that hot electron relaxation was dominated by the emission of confined phonon mode in the well rather than the interface phonon mode for wide GaAs/AlGaAs QWs. The hot electron–neutral acceptor luminescence experiments in the moderate wide InGaAs/GaAs strained QWs have shown evidences which are in good agreements with our calculations. However, the missing of the InAs-like and GaAs-like phonon peaks in the Raman spectrum of the strained QWs is still under investigation.

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