PERGAMON

Available online at www.sciencedirect.com
SCIENCE DIRECT®

Solid State Communications 126 (2003) 519–522

solid
state
communications

www.elsevier.com/locate/ssc

Inter- and intra-subband relaxation of hot electrons in GaAs/AlGaAs quantum wells

K.W. Sun[a,*], C.L. Huang[a], G.B. Huang[a], H.C. Lee[b]

[a]*Department of Physics, National Dong Hwa University, Da Sheuh Rd. Sec. 2, Shoufeng, Hualien, Taiwan, ROC*
[b]*Department of Electronics Engineering and Institute of Electronics, National Chiao Tung University, HsinChu, Taiwan, ROC*

Received 28 November 2002; accepted 19 March 2003 by H. Akai

Abstract

In this work, we have studied the inter- and intra-subband scattering of hot electrons in quantum wells using the hot electron–neutral acceptor luminescence technique. We have observed direct evidence of the emission of confined optical phonons by hot electrons excited slightly above the $n = 2$ subband in GaAs/Al$_{0.37}$Ga$_{0.63}$As quantum wells. Scattering rates of photoexcited electrons via inter- and intra-subband LO phonon emission were calculated based on the dielectric continuum model. We found that, for wide wells with the Al composition of our experiments, both the calculated and experimental results suggest that the scattering of the electrons is dominated by the confined LO phonon mode. In the calculations, scatterings among higher subbands are also dominated by the same type of phonon at well width of 10 nm.

PACS: 78.55; 78.30; 78.60; 78.66

Keywords: A. Quantum wells; D. Electron–phonon interactions; E. Inelastic scattering; E. Luminescence

1. Introduction

The critical role of phonons in semiconductor nanoscale devices is of great interest because of its important implications for many optoelectronic devices such as quantum well lasers, detectors and modulators. Polar optical phonon emission is believed to be the most efficient relaxation processes both in bulk [1] and quantum well structures [2–4]. Tatham and Ryan [5] have demonstrated that the inter-subband relaxation in narrow quantum wells is dominated by the interface phonon emissions. The inter-subband relaxation mechanism of photoexcited carriers in quantum wells at room temperature has also been studied using the infrared bleaching technique [6]. Using femtosecond resonant luminescence, Hartig et al. [7] reported the inter-subbband scattering rate of electrons in wide GaAs quantum wells at very low excitation densities.

Many calculations have been made in order to compare with those experimental results. For example, Goodnick and Lary [8] have made an ensemble Monte Carlo simulation of coupled electrons and holes in single and multiple quantum well systems. An energy-loss calculations involving slab phonon modes was reported in Ref. [9], which gives reasonable agreement with the experimental inter-subband relaxation rate. Ridley [10] has pointed out that electron–phonon scattering within a subband is affected principally by the interface mode with odd displacement symmetry, with a rate which increases with diminishing well width. More recently, Lee et al. [11] have studied the dynamics of intra-subband relaxation of hot electrons in GaAs/AlGaAs quantum wells with different structure parameters using dielectric continuum model (DCM). Their calculations were compared with the experimental results reported by Sun et al. [12,13]. It was found that the interface phonons play an essential role in the intra-subband relaxation process in the narrow quantum well structures.

In this study we report the direct observations of inter- and intra-subband relaxation through the emission of

---

* Corresponding author. Tel.: +886-3-8662500x21535; fax: +886-3-8662303.
E-mail address: kwsun@mail.ndhu.edu.tw (K.W. Sun).

0038-1098/03/$ - see front matter © 2003 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S0038-1098(03)00235-7

confined optical phonons in wide QWs using the hot electron–neutral acceptor luminescence technique. This technique has avoided the complications due to the presence of holes in the valence bands. We use this technique to determine the emitted optical phonon energy and mode. We also compared our measurements with numerical results based on DCM.

2. Experiments

Our samples were grown by molecular-beam epitaxy on (001) semi-insulating GaAs wafer and consist of forty wells with individual thickness of 10 nm. The center 5 nm were doped with Be to the density of about 10^{18} cm^{-3}. The wells are embedded in 40 nm thick of $Al_{0.37}Ga_{0.63}As$ layers. For the given structures, there were three confined subbands in the wells. The calculated energy separation between the $n = 1$(e1), $n = 2$(e2), and $n = 3$(e3) states in the conduction band are about 105 and 145 meV at the temperature of 4 K, respectively. The sample was kept at liquid helium temperature to ensure that all the acceptors were neutralized. The hot electrons were excited above the e2 subband of the QWs with excess kinetic energy less than the LO phonon energy using an argon ion laser pumped dye (with Pyridine dye) laser. The excited carrier densities were less than 1×10^9 cm^{-2}. The injected carrier densities were kept low so that the phonon emissions were the dominant relaxation processes for excited electrons. The electrons initially created on the $n = 2$ subbands can thermalized through the inter-subband scattering via LO phonon emissions. However, some of the electrons will reach the bottom of the e2 subband due to the carrier–carrier scattering or by emission of acoustic phonons. The electrons which have arrived at the bottom of e2 subband can either be scattered to e1 subband by the LO phonons or they can directly recombine with holes on the neutral acceptors and emit photons. For those electrons scattered to the e1 subband, they will continue to lose their energy by emitting LO phonons until their excess kinetic energy was below the LO phonon energy. During the relaxation processes, the electrons will recombine with the holes on the neutral acceptors [14] and emit photons. At the final stage, the hot electrons emit acoustic phonons to equilibrate with the lattice. The schematics of the possible transitions and the calculated confined subband energies are given in Fig. 1. The luminescence from the QWs was collected and time-integrated with a combination of a triplemate spectrometer and a liquid nitrogen cooled CCD detector. Therefore, we can sample the electron distributions on the conduction bands without the complications from the valence bands.

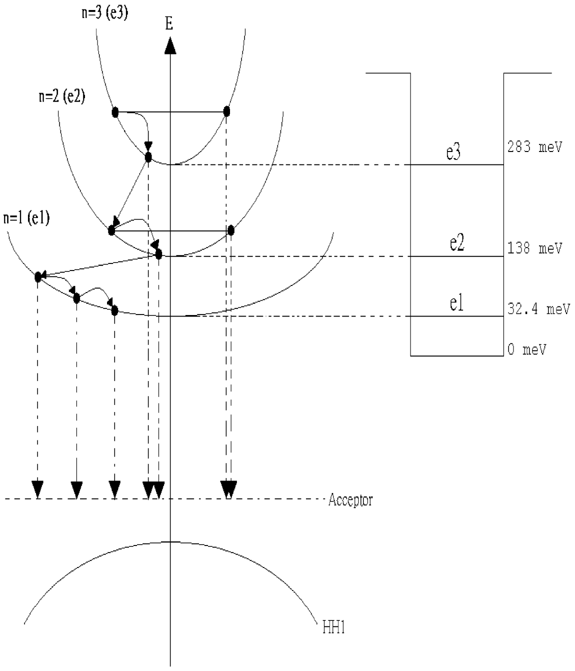

Fig. 1. Schematics of the possible transitions of photoexcited electrons in QWs and the calculated subband energies. The calculated values are plotted with respect to the conduction band minimum in bulk GaAs.

In Fig. 2 we show the major luminescence peaks at low temperature when the sample was excited with an argon ion laser operated at 514.5 nm. The bandgap energies of the wells and barriers at 10 K are at about 1.54 and 1.94 eV, respectively. The weaker luminescence peak below the band edge of the wells is due to the recombination of electrons at the ground state with holes on the acceptors.

The hot electron–neutral acceptor luminescence spectrum of the 10 nm QW sample obtained with the tunable dye laser as the excitation source is given in Fig. 3. The dye laser was operated at appropriate photon energies in order to give excess kinetic energies to electrons which is less than an LO

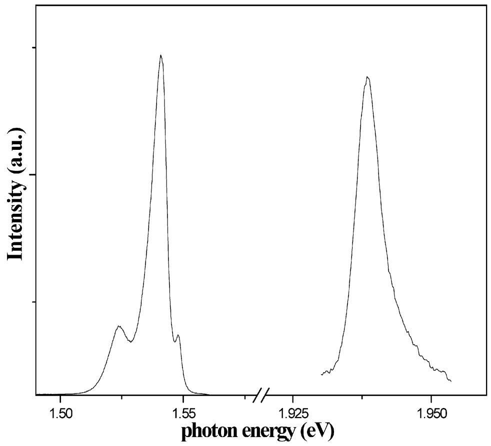

Fig. 2. Major luminescence peaks of the QW sample excited by an argon ion laser operated at 514.5 nm. The peak at 1.52 eV corresponds to the recombination of electrons at ground state with holes on neutral acceptors.

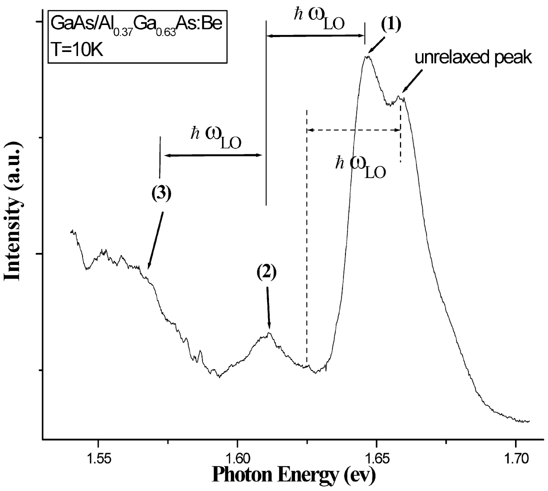

Fig. 3. Hot electron–neutral acceptor luminescence of the QWs excited by a Pyridine dye laser. The much stronger bandedge luminescence from the wells was intentionally blocked by a bandpass filter in the spectrometer.

phonon energy. The principles of this technique were explained in details in Ref. [14]. The peak labeled ‘unrelaxed peak’ in the spectrum corresponds to recombination of electrons, from the state at which they were initially created, with a neutral acceptor. The peak (1) represents electrons that have been scattered to the bottom of e2 subband and recombined with holes on the neutral acceptors. The peak labeled (2) was separated by one LO phonon energy with peak (1), which arise from those electrons that were scattered to the e1 subband from the bottom of e2 subband via inter-subband scattering with LO phonons and then recombined with holes on neutral acceptors. The peak labeled (3) was also separated by one LO phonon energy with peak (2), which was due to those electrons on e1 subband that have relaxed via successive LO phonon emission before recombining with neutral acceptors.

However, we did not resolve the phonon peak associated with the electrons that were scattered to the $n = 1$ subband via the LO phonon emission directly from the states at which they were initially created. We speculate that the missing peak in the spectrum is actually masked by the phonon peaks (1) and (2). This is due to the weaker oscillation strength for electrons away from the zone center, where the wavefunctions of the acceptors are also smaller.

In order to determine the energy separation between luminescence peaks more accurately, we first subtract the background and the energy spectra of the remaining peaks are then fitted by Gaussian distributions. The energy spacing between peaks (1), (2) and (3) is about 38 meV which is very close to confined phonon energy in GaAs/AlGaAs QWs. Therefore, our experimental results suggest that the confined phonon mode does played a dominant role in the electron–LO phonon interaction in wide QWs.

3. Calculations and discussion

In order to compare with our experimental results, we have calculated the electron–LO phonon inter-subband scattering rate as a function of well width in quantum wells using the DCM [15–18]. In the DCM, there are totally six types of optical-phonon modes in a dielectric slab. However, due to selection rules for the intra- and inter-subband scattering, only the confined LO mode, the half-space LO mode, and the symmetric interface modes were taken into consideration in our calculations. Electron–optical phonon interaction Hamiltonians for all modes in a dielectric slab are taken from the work of Ando and Mori [17]. 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 with states restricted by energy and momentum conservations. The details of our calculation method are given in Ref. [11].

In Fig. 4 we have plotted the electron–LO phonon 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 interface and confined phonon mode with odd potential symmetry. It is seen 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 interface 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

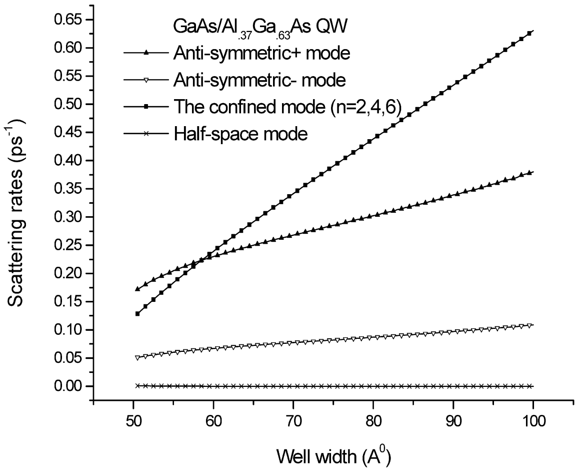

Fig. 4. Calculated electron–LO phonon inter-subband scattering rates as a function of well width.

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.

In our measurements, the average energy of the phonon that is emitted during the e2 to e1 subband transition is given by the energy separation between the luminescence peak (1) and (2), which is about 38 meV. This energy is very close to the energy of confined LO phonon in QWs, which is 37 meV. The interface phonon energy for the given Al composition in our experiments should be larger than 41 meV according to the measurements in Ref. [11,12]. Therefore, the dominant type of phonon mode emitted during the inter-subband scattering was identified to be the confined phonon. The measured results are in good agreement with the calculations at the well width that we have investigated.

The energy spacing between peaks (2) and (3) is also 38 meV. These two peaks are associated with the intra-band relaxation of hot electrons on the e1 subband. In contrast to the earlier experimental results in narrow QW structures [12,13], the intra-subband scattering is now dominated by the confined phonon as well. This conclusion is also consistent with the calculated intra-subband scattering rates reported in Ref. [11], where the scattering rate of the confined phonon is larger than the interface phonon at well width larger than 10 nm.

4. Conclusion

We have studied the inter- and intra-subband scattering of electrons in GaAs/$Al_{0.37}Ga_{0.63}As$ quantum well structures using the hot electron–neutral acceptor luminescence technique. The inter- and intra-subband transitions are both dominated by the confined LO phonons at the well width that we have investigated. Calculated results on the dependence of the scattering rates on well width also support our measurements.

Acknowledgements

This work is supported by the National Science Council under Grant No. NSC91-2120-E-259-001 and NSC91-2112-M-259-016.

References

[1] D. von Der Linde, R. Lambrich, Phys. Rev. Lett. 42 (1979) 1090.

[2] J. Shah, IEEE J. Quantum Electron 22 (1986) 1728.

[3] J.F. Ryan, R.A. Taylor, A.J. Turberfield, A. Maciel, J.M. Worlock, A.C. Gossard, W. Wiegmann, Phys. Rev. Lett. 53 (1984) 1841.

[4] W.H. Knox, R.L. Fork, M.C. Downer, D.A.B. Miller, D.C. Chemla, C.V. Shank, Phys. Rev. Lett. 45 (1985) 1306.

[5] M.C. Tatham, J.F. Ryan, Semicond. Sci. Technol. 7 (1992) B102.

[6] A. Seilmeier, H.-J. Hübner, G. Abstreiter, G. Weimann, W. Schlapp, Phys. Rev. Lett. 59 (1987) 1345.

[7] M. Hartig, S. Haacke, P.E. Selbmann, B. Deveaud, Phys. Rev. Lett. 80 (1998) 1940.

[8] S.M. Goodnick, J.E. Lary, Semicond. Sci. Technol. 7 (1992) B109.

[9] J.K. Jain, S. Das Sarma, Phys. Rev. Lett. 62 (1989) 2305.

[10] B.K. Ridley, Phys. Rev. B39 (1989) 5282.

[11] H.C. Lee, K.W. Sun, C.P. Lee, J. Appl. Phys. 92 (2002) 268.

[12] K.W. Sun, H.Y. Chang, C.M. Wang, T.S. Song, S.Y. Wang, C.P. Lee, Solid State Commun. 115 (2000) 563.

[13] K.W. Sun, C.M. Wang, H.Y. Chang, S.Y. Wang, C.P. Lee, J. Lumin. 92 (2001) 145.

[14] B.P. Zakharchenya, P.S. Kop'ev, D.N. Mirlin, D.G. Polakov, I.I. Reshina, V.F. Sepega, A.A. Sirenko, Solid State Commun. 69 (1989) 203.

[15] R. Fuchs, K.L. Kliewer, Phys. Rev. 140 (1965) A2076.

[16] J.J. Licari, R. Evrard, Phys. Rev. B15 (1977) 2254.

[17] N. Mori, T. Ando, Phys. Rev. B40 (1989) 6175.

[18] R. Chen, D.L. Lin, T.F. George, Phys. Rev. B41 (1990) 1435.