



Ultrafast carrier–carrier scattering in $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ quantum wells

K.W. Sun^{a,*}, T.S. Song^a, C.-K. Sun^b, J.C. Wang^b, S.Y. Wang^c, C.P. Lee^c

^a*Department of Electronic Engineering, Feng Chia University, Taichung, Taiwan, ROC*

^b*Graduate Institute of Electro-Optical Engineering, National Taiwan University, Taipei, Taiwan, ROC*

^c*Department of Electronics Engineering and Institute of Electronics, National Chiao Tung University, Hsin Chu, Taiwan, ROC*

Abstract

We present new time-resolved measurements that demonstrate the effect of injected carrier densities on carrier–carrier scattering rates of a highly nonequilibrium carrier distribution in the p-doped $\text{Al}_{0.32}\text{Ga}_{0.68}\text{As}/\text{GaAs}$ quantum wells. The initially photoexcited nonthermal carrier distribution is quickly broadened due to rapid increase of the inelastic carrier–carrier scattering as the injected carrier densities increased toward 10^{11} cm^{-2} . © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Carrier–carrier scattering; LO phonon emission; Nonthermal carrier distributions

Recently, femtosecond optical spectroscopy has proven to be an excellent tool for the study of fundamental nonequilibrium properties in semiconductors [1–6]. While there are still questions remaining, it appears safe to say that hot-electron relaxation in bulk GaAs is becoming relatively well understood. However, in 2D the situation is quite murky. Less experimental data on carrier–carrier scattering rates are available for 2D carriers than 3D carriers. Kash has studied the energy loss rate of a hot electron to a thermalized electron–hole plasma in $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ quantum wells [7]. The experimental situation of nonthermal carrier distributions in 2D has been dominated by four experiments of Knox and coworkers [4,8]. In this report we have made a time-resolved measurement

of the distribution at densities below 10^{10} cm^{-2} . We excited the sample with an ultrafast optical pulse and measured the time-integrated hot(e, A) luminescence spectra as a function of photoexcited carrier densities. We are not only able to inject a moderate density of carriers into the sample but are also able to create a highly nonequilibrium distribution of hot carriers with our 120 fs duration pulses because LO phonon emission by the photoexcited carrier is not large during the laser pulses. By measuring the first unrelaxed peak in the hot(e, A) luminescence spectra, we are assured of sampling the hot electron distribution within an LO phonon emission time (~ 150 fs) [9–12].

The MQW samples studied here were 5 nm GaAs wells, with $x = 0.32$ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ barrier of 25 nm thickness. The quantum wells were doped with Be in the central 1 nm of each wells to 10^{18} cm^{-3} . The quantum-well samples consisted of a stack of 40 wells and were grown on [1 0 0]

*Corresponding author. Tel.: 886-4-4517250 ext 3877; fax: 886-4-4510405.

E-mail address: kwsun@fcu.edu.tw (K.W. Sun)

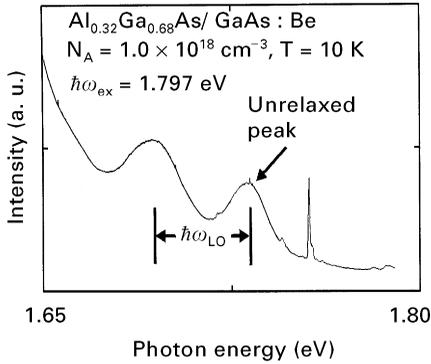


Fig. 1. Time-integrated luminescence of 5 nm quantum wells after CW excitation at 1.797 eV.

undoped GaAs substrates. For all experiments reported here, the samples were held in a closed-cycled cryostat refrigerator at $T = 10$ K to ensure that virtually all the acceptors are neutral and to reduce the occupancy of LO phonon to insignificant levels. Hot(e , \AA) luminescence spectra are taken with the combination of a triplemate spectrometer and a liquid nitrogen cooled CCD detector. The experiments have employed two excitation sources – an argon ion laser pumped CW dye laser and a self-mode-locked Ti:sapphire laser. The CW dye laser was operated at an energy of 1.797 eV and the self-mode-locked Ti:sapphire laser which generated optical pulses as short as 120 fs was operated at the same energy with a 80 MHz repetition rate.

Fig. 1 shows the time-integrated luminescence spectrum with the dye laser used as the excitation source. In Fig. 1, the “unrelaxed peak” in the spectrum is due to the initial unrelaxed hot electrons excited from the lowest heavy-hole band recombining with neutral acceptors. It clearly shows that, under CW excitation, the electrons have relaxed through successive LO phonon emission events before recombining with neutral acceptor.

In Fig. 2 we show spectra obtained with the self-mode-locked Ti:sapphire laser as the excitation source. By defocusing the laser, the injected carrier density can be varied from 1×10^9 to $2 \times 10^{11} \text{ cm}^{-2}$. The photoexcited carrier densities are determined from the laser spot size on the sample (through a periscope arrangement behind the entrance slit in the spectrometer) and the absorption

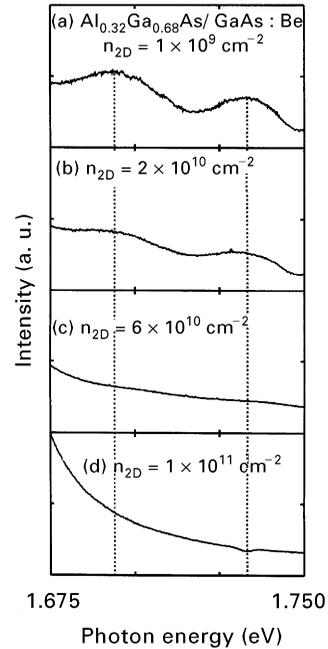


Fig. 2. Time-integrated luminescence of 5 nm quantum wells after femtosecond excitation at 1.797 eV for various injected carrier densities.

coefficient of the QW samples at the excitation wavelength. Our detection system is adjusted to sample only the center half of the laser spot, thus minimizing uncertainties associated with non-uniform injection. We have also compared our estimated carrier densities with those differential-transmission type experiments in which the absorption depth can be accurately determined. Our estimations of the injected carrier densities are within an error factor of two (carrier diffusion can be ignored on the femtosecond time scale). The corresponding spectra of injected carrier densities from $1 \times 10^9 \text{ cm}^{-2}$ to $2 \times 10^{11} \text{ cm}^{-2}$ are shown in Fig. 2(a)–(d). The unrelaxed peaks begin to decrease at a carrier density of $1 \times 10^9 \text{ cm}^{-2}$. As the injected carrier density is increased toward $1 \times 10^{11} \text{ cm}^{-2}$, the peaks disappear. The height of the unrelaxed peak measures the density of electrons at the initial energy convolved with broadening mechanism such as acceptor–acceptor interactions. We find no change in the line width of the peak, and thus measurements of the integrated area under the

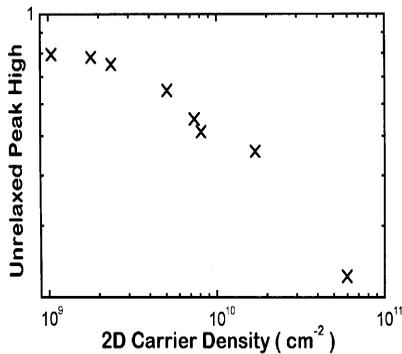


Fig. 3. The unrelaxed peak intensities (relative to the background) in each spectrum taken in the Ti : sapphire laser experiments are plotted as the function of injected carrier densities.

peak give the same results as measuring the peak height. In Fig. 3 we plot the unrelaxed peak intensity relative to the background (which remains relatively constant) in each spectrum as a function of injected carrier density. The probability that an electron will be scattered out of this peak before emitting an LO phonon is small if, during an LO phonon emission time, scattering transfers little energy among carriers relative to the width of the peak. Thus at low densities the unrelaxed peak is unaffected by carrier–carrier scattering. At higher densities, however, the interactions among carriers are stronger, and at sufficiently high densities carrier–carrier scattering will reduce the height of the unrelaxed peak. The height of the unrelaxed peak thus allowed us to compare the relative importance of carrier–carrier scattering and LO phonon emission for the scattering of energetic electrons. We interpret the decrease of the unrelaxed peak, as the injected carrier density is increased, as evidence that carrier–carrier scattering is becoming important [13,14].

Our results are in qualitative agreement with Kane's [15] theoretical works in which he has studied the carrier–carrier scattering using integration of the dynamically screened Boltzmann equation. In his studies, 2D electron–hole pairs are generated in GaAs with an average energy of 20 meV, and an average hole energy of 12 meV. The initial energy width (FWHM) of the electron peak is 20 meV. The evolution of the electron distribu-

tion is followed for 150 fs. The initial electron peak height dropped by a factor of two as the density was increased to $5 \times 10^{10} \text{ cm}^{-2}$. In our experiments, by interpolation, we find that at an injected carrier density of $1 \times 10^{10} \text{ cm}^{-2}$ the intensity drops by a factor of two compared to the CW experiment. The slight difference between the experimental results and calculations is probably due to the higher electron excess energy for the photoexcited carriers in the experiments.

In conclusion, our experimental results show that at an injected density lower than $1 \times 10^{10} \text{ cm}^{-2}$ the hot electrons lose their energy to the lattice before being affected by carrier–carrier scattering. As the carrier density is increased from 1×10^9 to $2 \times 10^{11} \text{ cm}^{-2}$, however, the carrier–carrier scattering begins to compete with carrier–phonon scattering. At carrier densities greater than $1 \times 10^{11} \text{ cm}^{-2}$, carrier–carrier scattering is the dominant scattering process.

Acknowledgements

This work was supported by the National Science Council of Republic of China under contract Grant No. NSC87-2112-M-035-004 and NSC86-2112-M-035-008.

References

- [1] D.W. Snoke, W.W. Ruhle, Y.C. Lu, E. Bauser, *Phys. Rev. Lett.* 68 (1992) 990.
- [2] D.W. Snoke, W.W. Ruhle, Y.C. Lu, E. Bauser, *Phys. Rev. B* 45 (1992) 10979.
- [3] A. Leitenstorfer, C. Furst, Alaubereau, W. Kaiser, *Phys. Rev. Lett.* 76 (1996) 1545.
- [4] W. Knox, C. Hirlimann, D.A.B. Miller, J. Shah, D.S. Chemla, C.V. Shank, *Phys. Rev. Lett.* 56 (1986) 1191.
- [5] T. Elsaesser, J. Shah, L. Rota, P. Lugli, *Phys. Rev. Lett.* 66 (1991) 1757.
- [6] J. Shah, B. Deveaud, T.C. Damen, W.T. Tsang, A.C. Gossard, P. Lugli, *Phys. Rev. Lett.* 59 (1987) 2222.
- [7] J.A. Kash, *Phys. Rev. B* 48 (1993) 18336.
- [8] W.H. Knox, D.S. Chemla, G. Livescu, J.E. Cunningham, J.E. Henry, *Phys. Rev. Lett.* 61 (1988) 1290.
- [9] B.P. Zakharchenya, P.S. Kop'ev, D.N. Mirlin, D.G. Polakov, I.I. Reshina, V.F. Sapega, A.A. Sirenko, *Solid State Commun.* 69 (1989) 203.
- [10] C.V. Shank, R.L. Fork, R. Yen, J. Shah, B.I. Greene, A.C. Gossard, C. Weisbuch, *Solid State Commun.* 47 (1983) 981.
- [11] J. Shah, *IEEE J. Quantum Electron.* QE-22 (1986) 1728.

- [12] D. Collings, K.L. Schumacher, F. Raksi, H.P. Hughes, R.T. Philips, *Appl. Phys. Lett.* 64 (1994) 889.
- [13] K.W. Sun, M.G. Kane, S.A. Lyon, *Europhys. Lett.* 26 (1994) 123.
- [14] A. Leitenstorfer, T. Elsaesser, F. Rossi, T. Kuhn, W. Klien, G. Boehm, G. Traenkle, G. Weimann, *Phys. Rev. B* 53 (1996) 9876.
- [15] M.G. Kane, *Phys. Rev. B* 54 (1996) 16354.