Available online at www.sciencedirect.com

SCIENCE DIRECT®

Physica E 22 (2004) 312–315

PHYSICA E

www.elsevier.com/locate/physe

Transport and quantum lifetime dependence on electron density in gated GaAs/AlGaAs heterostructures

Tse-Ming Chen[a,*], C.-T. Liang[a], M.Y. Simmons[b,c], Gil-Ho Kim[b,d], D.A. Ritchie[b]

[a] Department of Physics, National Taiwan University, Taipei 106, Taiwan
[b] Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, United Kingdom
[c] School of Physics, University of New South Wales, Sydney 2052, Australia
[d] Department of Electronic and Electrical Engineering, Sungkyunkwan University, Suwon 440-760, South Korea

Abstract

We present a study of the transport and quantum lifetime dependence on electron density in two completely different kinds of two-dimensional electron gas systems. We observed that both the two scattering time increase with increasing the electron density. But the ratios of the transport to the quantum lifetime have different tendency with the electron density, which do not conform to the conventional theory. We speculate that the screening effects need to be considered in order to explain our experimental results.

PACS: 73.40−c; 73.43−f

Keywords: Lifetime; Small angle scattering; Ionized donors

In the two-dimensional electron gas (2DEG) various lifetimes are introduced by a finite amount of disorder. Electron transport in semiconductors is generally characterized by a transport lifetime τ_t, which is defined by the relaxation-time approach to the Boltzmann equation and is related to the conductivity, through $\sigma = n_s e^2 \tau_t / m^*$. However, there is a quantum lifetime (single-particle relaxation time) τ_q describing the decay time of one-particle excitations and characterizing the quantum-mechanical broadening of the single-particle electron state [1–3]. The quantum lifetime τ_q and the transport lifetime τ_t are given by [2,4]

$$\frac{1}{\tau_q} = \frac{m^*}{\pi\hbar^3} \int_0^\pi \mathrm{d}\theta |V(q)|^2, \tag{1}$$

$$\frac{1}{\tau_t} = \frac{m^*}{\pi\hbar^3} \int_0^\pi \mathrm{d}\theta |V(q)|^2 (1 - \cos\theta), \tag{2}$$

with $q = 2k_F \sin(\theta/2)$, and $k_F = \sqrt{2\pi n_s}$. $|V(q)|$ is the probability of scattering through an angle θ from a state $\mathbf{k}$ to a state $\mathbf{k}'$ on the Fermi circle. For a short-range scattering potential τ_t and τ_q are approximately equal [5]. But for modulation-doped GaAs/AlGaAs heterostructures, where the dominate scattering mechanism is the long-range potential associated with ionized donors which are far from the 2D EG and which produce predominantly small-angle scattering, τ_q will be much smaller than τ_t since

---

[*] Corresponding author. Tel.: +886-2-3366-5101; fax: +886-2-2363-9984.

E-mail address: tseming@ntu.edu.tw (T.-M. Chen).

1386-9477/$ - see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.physe.2003.12.009

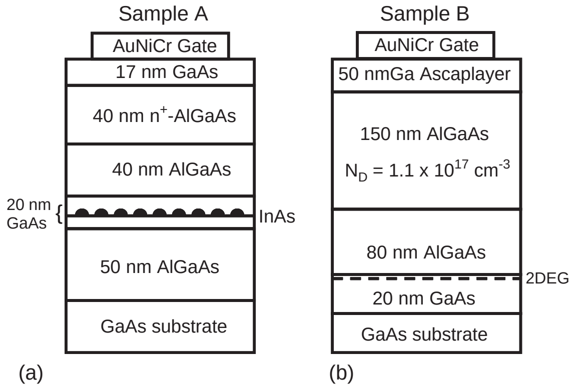

Fig. 1. Schematic cross section of the experimental sample structures. (a) Sample A: GaAs/AlGaAs heterostructures in which InAs self-assembled quantum dots have been inserted, (b) Sample B: conventional GaAs/AlGaAs heterostructures but with thicker spacer layer.

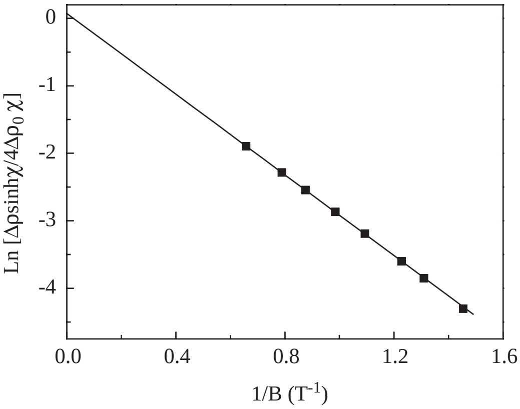

Fig. 2. Dingle plot of sample A at $V_g = 0$. The intercept passes through the origin and the slope gives $1/\tau_q$.

the $(1 - \cos\theta)$ weighting factor diminishes at small angle θ.

Though several studies of τ_q in GaAs/AlGaAs heterostructures with different transport mobilities and electron densities have been reported [3,6–9], to data there seems to have been no systematic studies of transport and quantum lifetime dependence on electron density. It is well known that at liquid helium temperature, the distribution and density of ionized donors remain constant. Therefore, by measuring a gated GaAs heterostructure, one can study both the transport and quantum lifetime as a function of electron density at a *fixed* ionized donors' distribution and density, and it is the purpose of this paper to report such measurements.

The samples investigated in this experiment were gated modulation doped GaAs/AlGaAs heterostructures grown by molecular beam epitaxy (MBE). Fig. 1 shows the schematic cross section of the two samples. For sample A, an InAs layer was grown into the GaAs quantum well to increase the disorder experienced by 2DEG so that the dominate scattering mechanism would be the short-range potential associated with the InAs quantum dots. It is well known that ionized impurity scattering has been known to represent the main scattering mechanism at zero temperature, whereas alloy disorder and surface roughness are weak. To investigate the effects of carrier density on the single-electron relaxation time in the circumstance in which the small-angle scattering dominates, we use sample B with high mobility up to 300 $\mathrm{m^2/V\ s}$ in this experiment as a consequence from the 80 nm undoped $Al_{0.33}Ga_{0.67}As$ spacer layer, which is thicker than the conventional undoped spacer. Magneto-transport measurements were performed with a top-loading He^3 system and a superconductor magnet. The low-frequency AC lock-in technique with the current of 10 nA applied to the samples was used in this work.

Both from the Hall and Shubnikov–de Haas (SdH) measurements, the carrier density of 2DEG was obtained. The transport lifetime τ_t is calculated from the zero magnetic field longitudinal conductivity σ_{xx}, whereas the quantum lifetime is related to the SdH amplitude of the oscillations and can be experimentally determined from Dingle plots. In the low field the amplitude of the SdH oscillations is given by [7]

$$\Delta\rho = 4\rho_0 \frac{\chi}{\sinh\chi} \exp\left[-\frac{\pi}{\omega_c \tau_q}\right],$$

where ρ_0 is the zero-field resistivity, ω_c the cyclotron frequency, and $\chi = 2\pi^2 kT/\hbar\omega_c$. In a Dingle plot, the logarithm of $\Delta\rho \sinh\chi/4\rho_0\chi$ is plotted against $1/B$, which is a straight line and the slope gives $1/\tau_q$ directly with an intercept of zero. A typical Dingle plot obtained in this work is shown in Fig. 2. The quantum lifetimes were obtained from Dingle plots at different gate voltages (carrier density).

Fig. 3 shows the variation of the measured values of transport and quantum lifetime with the 2DEG density for sample A. Both τ_t and τ_q increase with

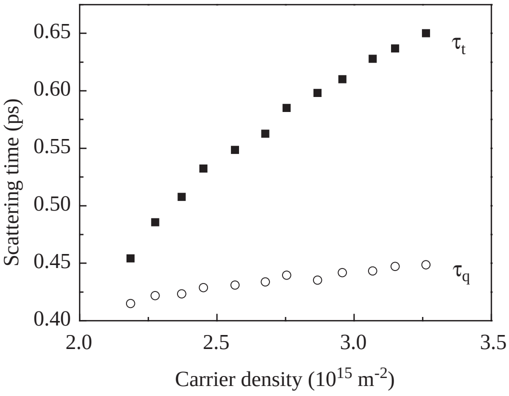

Fig. 3. The transport and quantum lifetime (sample A) measured from Dingle plots is plotted against carrier density.

increasing carrier density. It should be noted that the quantum lifetime varies little and is almost constant with increasing the carrier density as reported previously [8,9]. Besides, the ratio of the transport to quantum lifetime is smaller than 2 so that we could assure that the short-range scattering dominate the 2DEG as a consequence of the InAs self-assembled quantum dots. For the transport lifetime of sample B shown in Fig. 4(a), we observe that τ_t decreases with decreasing electron density and shows a linear dependence on electron density. It is consistent with the theory and all the previous experiment results. But for quantum lifetime, unlike the τ_q dependence on electron density of sample A and the previous reports [8,9] that the variation of τ_q is much smaller than the variation of τ_t and is practically negligible no matter τ_q slightly increases or decreases with increasing the carrier density, our results show that the quantum lifetime τ_q shows an exponential increase with increasing electron density, as shown in Fig. 4(b). Fig. 4(b) shows that the increasing of τ_q with electron density is small while carrier density is below about 1.35×10^{15} m^{-2}. But while n_e is above 1.35×10^{15} m^{-2}, τ_q increases by 3 times. An empirical fit was obtained that is given by $\tau_q = 1.261 + 1.25 \times 10^{-18} \exp(2.85 \times 10^{-14} n_e)$ (ps). The substantial increase of τ_q with increasing n_e could probably be interpreted in terms of models concerned with the increase in electron screening of the long-range random potential induced by the remote ionized donors [10]. But for τ_t, because of the weighting factor $(1 - \cos\theta)$, the effect of the electron screening would suppress in the scattering rate. Moreover, it may be noted that both τ_t and τ_q is much larger than that of the highly disorder GaAs/AlGaAs heterostructure (sample A).

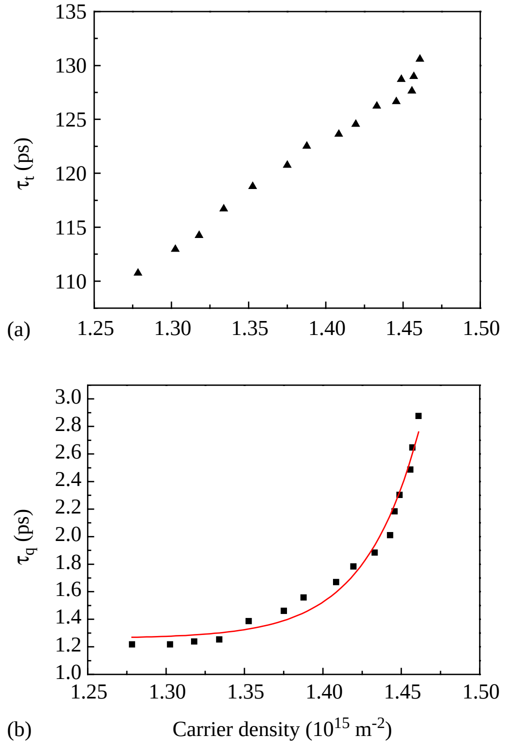

Fig. 4. (a) The transport lifetime as a function of carrier density. (b) The quantum lifetime as a function of carrier density. The quantum lifetime has an exponential increase as carrier density. The exponential fit is $\tau_q = 1.261 + 1.25 \times 10^{-18} \exp(2.85 \times 10^{-14} n_e)$ (ps).

Fig. 5 shows the ratio of the transport to quantum lifetime increase from about 45 to 90 with decreasing electron density. It can be seen that the reason why the ratio increases with increasing the carrier density is the drastic increasing of the quantum lifetime with carrier density. The theoretical calculations of the ratio of the transport to quantum lifetime could be easily made with the analytical formalism given by $\tau_t/\tau_q = (2k_F S)^2$, with S the thickness of the spacer layer [11]. The dashed line in Fig. 5 shows the numerical calculations by the theory. The large discrepancy between the experimental data and the theoretical predictions is based on that the multiple small-angle scattering events

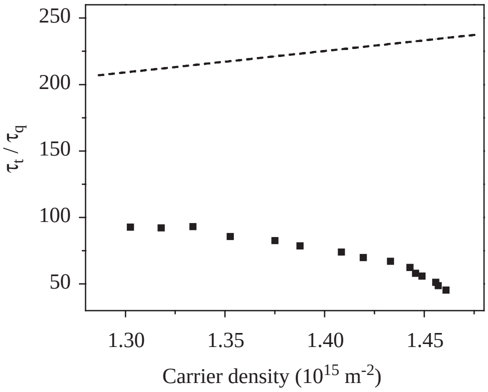

Fig. 5. The ratios τ_t/τ_q are plotted against carrier density. The theoretical cure (dashed line) for $\tau_t/\tau_q = (2K_F S)^2$ is also shown.

produced by those remote ionized donors are treated as statistically correlated instead of independent [3,12–14]. But, even considering the correlation correction, the theoretical predictions of the ratio also increase with increasing carrier density, which has similar tendency like the dashed line in Fig. 5. The reason for this is not known at present, but we speculate that the screening effect needs to be considered in order to explain our experimental results.

In summary, we have studied the transport and quantum lifetimes of the 2DEG in the two entirely different GaAs/AlGaAs heterostructures. For the GaAs heterostructure with InAs self-assembled quantum dots, the transport and quantum lifetimes and the ratio of them are much smaller than those of the conventional GaAs heterostructure. But for the GaAs heterostructure with mobility up to 300 m^2/V s, the ratio is much larger than that in the previous reports. The substantial increase of the quantum lifetime with carrier density were observed and interpreted in terms of the electron screening effect. We also showed that the tendency of the ratio τ_t/τ_q do not agree with the theoretical predictions and require further investigation.

This work was funded by the NSC, Taiwan. The work at Cambridge was funded by the EPSRC, United Kingdom. Gil-Ho Kim was supported by National R&D Project for Nano Science and Technology (Contract No. M1-0212-04-0003) of MOST. C.T.L. thanks T. Chin for her support.

References

[1] T. Ando, J. Phys. Soc. Japan 51 (1982) 3900.
[2] T. Ando, A. Fowler, F. Stern, Rev. Mod. Phys. 54 (1982) 437.
[3] P.T. Coleridge, Phys. Rev. B 44 (1991) 3793.
[4] G. Bastard, Wave Mechanics Applied to Semiconductor Heterostructures, Les Editions de Physique, Les Ulis, France, 1988.
[5] F.F. Fang, A.B. Fowler, A. Hartstein, Phys. Rev. B 16 (1977) 4446.
[6] J.P. Harrang, R.J. Higgins, R.K. Goodall, P.R. Jay, M. Laviron, P. Delescluse, Phys. Rev. B 32 (1986) 8126.
[7] P.T. Coleridge, R. Stoner, R. Fletcher, Phys. Rev. B 39 (1989) 1120.
[8] U. Bockelmann, G. Abstreiter, G. Weimann, W. Schlapp, Phys. Rev. B 41 (1900) 7864.
[9] B. Das, S. Subramaniam, M.R. Melloch, D.C. Miller, Phys. Rev. B 47 (1993) 9650.
[10] A.L. Efros, Solid State Commun. 70 (1989) 253.
[11] A. Gold, Phys. Rev. B 38 (1988) 10798.
[12] B.K. Ridley, Semicond. Sci. Technol. 3 (1987) 111.
[13] R. Lassning, Solid State Commun. 65 (1988) 765.
[14] P.J. van Hall, Superlatt. Microstruct. 6 (1989) 213.