RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 37, NUMBER 8 15 MARCH 1988-I

Study of the single-particle and transport lifetimes in GaAs/$Al_xGa_{1-x}As$

R. G. Mani and J. R. Anderson

Joint Program for Advanced Electronic Materials, Department of Physics, University of Maryland
and Laboratory of Physical Sciences, College Park, Maryland 20742

(Received 16 November 1987)

We report a large discrepancy between the measured and theoretically predicted Fermi wave-vector dependence of the transport lifetime to single-particle lifetime ratio for a modulation-doped GaAs/$Al_xGa_{1-x}As$ heterostructure when the carrier density is varied by thermally cycling the sample, grown using molecular-beam epitaxy (MBE), after illumination by a light pulse. The results suggest that the deep centers responsible for the persistent photoconductivity effect, which may originate from nonstoichiometric MBE growth, are the dominant factor in limiting the single-particle lifetime in GaAs/$Al_xGa_{1-x}As$.

Artificially structured materials have led to the realization of systems of reduced dimensionality and thus new phenomena such as the quantum Hall effect (QHE).[1] The high degree of control exercised over these materials has produced greater expectation for agreement between theory and experiment and also for consistency among different experiments in such systems compared to conventional bulk semiconductor systems.

A review of the QHE literature shows that although the quantization of the Hall plateaus and the corresponding zero-resistance state are consistently observed by all experimenters, details such as the magnitude of the Shubnikov-de Haas (SdH) oscillations, the critical current for breakdown of QHE, and the current dependence of the asymmetry of the SdH spin-split peaks are not consistent among different experimenters.[1,2] In addition, the study of the QHE in GaAs/$Al_xGa_{1-x}As$ has been impeded by uncontrollable changes in sample properties due to thermal cycling but this effect has not been investigated nor understood to our knowledge.

Our study of QHE, to be reported elsewhere, revealed that the day-to-day variations in the sample properties due to thermal cycling could be reversed using light pulses. We are able to determine the origin of these variations by studying the carrier density dependence of the transport lifetime and the single-particle lifetime, and comparing with theoretical predictions for an ideal modulation-doped system. There is a large discrepancy between the measured Fermi wave-vector dependence of the transport lifetime to single-particle lifetime ratio and the theoretical prediction of Das Sarma and Stern,[3] which suggests that the deep centers responsible for the persistent photoconductivity (PPC) effect cause the apparent metastability of the sample and also are the dominant factor in limiting the single-particle lifetime in real systems.

Transport measurements can be used to determine two characteristic relaxation times, the transport lifetime τ_t, and the single-particle lifetime τ_s. The transport lifetime is defined by the solution of the Boltzmann equation in the relaxation time approximation. It is related to the dc conductivity σ, through $\sigma = N_s e \mu = N_s e^2 \tau_t / m^*$. Here, N_s is the two-dimensional sheet carrier density, μ is the Hall mobility, and m^* is the electron effective mass. The single-particle lifetime becomes finite in the presence of perturbations produced by scattering potentials and is related to the half-width Γ of the broadened Landau level through $\Gamma = \hbar / 2\tau_s$.

The transport and single-particle lifetimes are not equal due to the presence of an extra $(1-\cos\theta)$ factor in the expression for τ_t, i.e.,

$$1/\tau_t = \int dk' P(k,k')(1-\cos\theta) \ , \tag{1}$$

$$1/\tau_s = \int dk' P(k,k') \ . \tag{2}$$

Here, $P(k,k')$ is the probability for scattering from state k to state k', and θ is the scattering angle. Therefore, τ_t is insensitive to small-angle scattering while τ_s is sensitive to all scattering events. In systems where the scattering is mostly small angle, the transport to single-particle lifetime ratio can be large, $\tau_t/\tau_s > 1$. Conversely, in systems with isotropic scattering $\tau_t/\tau_s = 1$.

Experimentally, the single-particle lifetime is determined through a line-shape fit to the low-field Shubnikov-de Haas (SdH) oscillations. Dingle[4] originally observed that the effect of increased scattering upon the SdH line shape is equivalent to increasing the sample temperature. An effective sample temperature, T_{eff}, can be defined in terms of the Dingle temperature T_D, where $T_{\text{eff}} = T + T_D$, and the Dingle temperature is related to the single-particle lifetime through $\tau_s = \hbar / 2\pi k_B T_D$.

For two-dimensional systems, Ando[5,6] has derived an expression for SdH oscillations of the diagonal conductivity, σ_{xx}, due to scattering by short-range potentials. As we have limited the present study to low fields such that $2\pi^2 k_B T / \hbar\omega \gtrsim 1$, here ω is the cyclotron frequency, and also because the experimentally measured quantity are the SdH oscillations in the resistivity, ρ, rather than σ_{xx}, we have chosen to fit the data to the following semiempirical expression:

$$\rho = \rho_0 + A e^{-\lambda(T+T_D)(m^*/m)/B} \cos(2\pi F/B + \phi) \ , \tag{3}$$

which approximates Ando's results to within a polynomial in H prefactor. Here, $\lambda = 146.9$ kOe/K, F is the SdH frequency in kOe, and B is the applied field in kOe. We have determined that neglecting a first- or second-order polynominal in B prefactor results in a 5%–10% systematic error in the value for T_D but does not affect the shape of the experimental curves.

We report measurements made on a single Van der Pauw pattern which was photolithographically inscribed on an MBE GaAs/Al$_x$Ga$_{1-x}$As heterostructure grown at Martin Marietta Laboratories. The sample consisted of 1 μm of intrinsic GaAs on a Cr-doped GaAs substrate followed by 250 Å of intrinsic Al$_{0.3}$Ga$_{0.7}$As, 500 Å layer of Si-doped (8×10^{17} cm^{-3}) Al$_{0.3}$Ga$_{0.7}$As, and capped by 200 Å of Si-doped (2×10^{18} cm^{-3}) GaAs. The sample was immersed in pumped liquid helium at $T=1.55$ K for all measurements reported here.

The experimental procedure was as follows: The sample was initially exposed to a light pulse from a red light-emitting diode (LED) and then kept at ~200 K for 12 h before it was cooled to 1.5 K for transport measurements. The thermal cycling was repeated several times before the sample was reexposed to a light pulse. The results were observed to reproduce through several sequences of this process.

We have observed that the variation of the sample characteristics even in the quantum Hall regime, due to thermal cycling, originates from the deep defects that cause the persistent photoconductivity effect. Thus, these effects can be reproduced by subjecting the sample to short (~1 sec) light pulses from a red LED at low temperatures followed by thermal cycling. We determine the effect of thermal cycling by comparing the changes in τ_s, τ_t, and N_s. Although τ_s and τ_t have been compared by others[7,8] in the GaAs/Al$_x$Ga$_{1-x}$As system using different samples, the variation of these quantities versus N_s in a single sample had not been studied previously to our knowledge.

The Hall mobility was determined from low-field Van der Pauw resistivity measurements and then converted to the mobility temperature using $T_\mu = e\hbar/2\pi k_B m^* \mu$, assuming $m^*/m=0.069$ for GaAs/Al$_x$Ga$_{1-x}$As.[9] In Fig. 1, we have plotted the mobility temperature as a function of the carrier density. The figure indicates that the mobility temperature increases as the carrier density decreases with thermal cyclng. The data shown in the figure are for several sequences of exposing the sample to light followed by repeated thermal cycling. The mobility of the sample could be varied over the range 120000 cm^2/Vs $<\mu<$ 300000 cm^2/Vs. Usually, it is observed that the

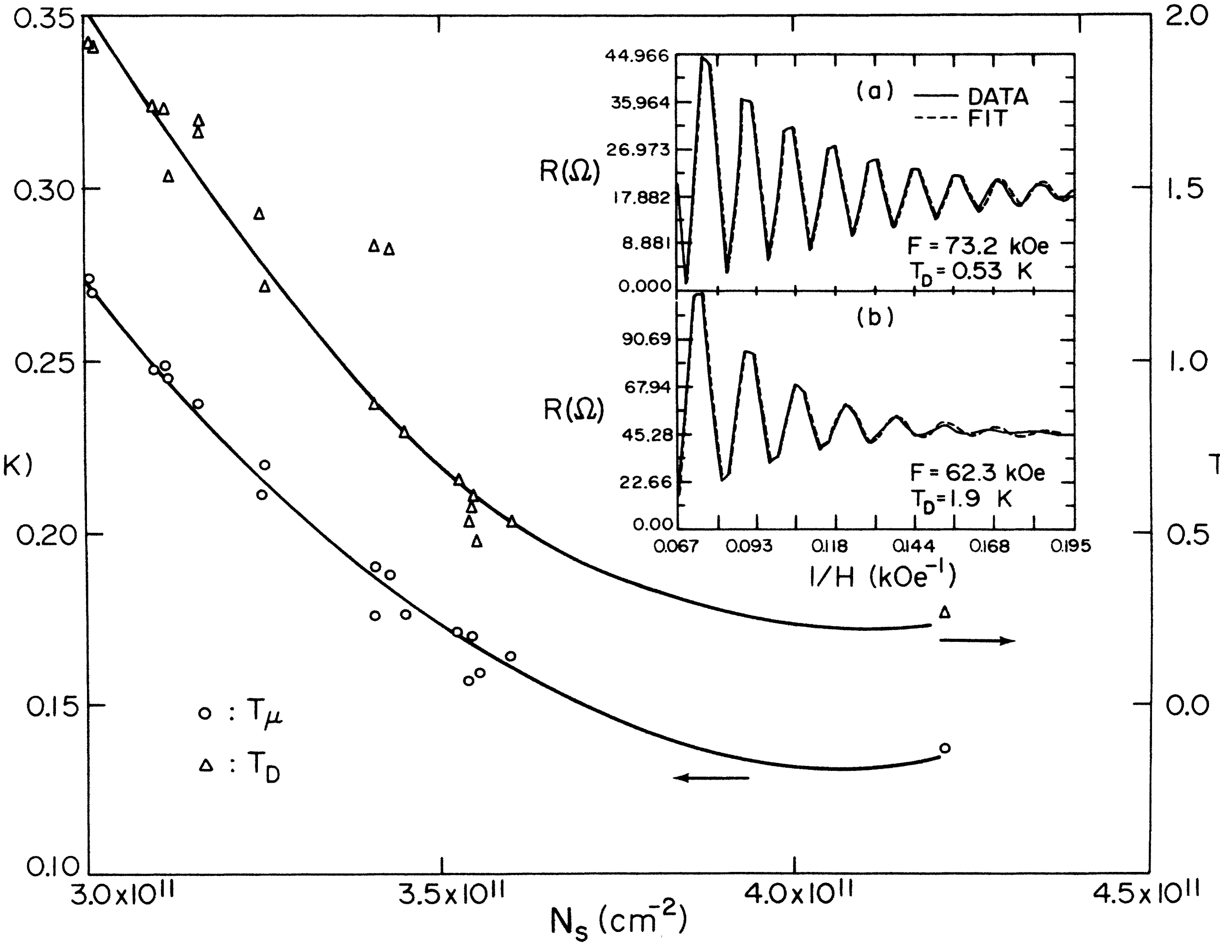

FIG. 1. The mobility and Dingle temperatures are plotted as a function of the two-dimensional sheet carrier density. In the inset, we have shown the data and fit to the low-field Shubnikov-de Haas oscillations for (a) high and (b) low mobility data. Also shown in the inset are the SdH frequency F, and the Dingle temperature T_D, obtained from the fit.

carrier density and the mobility can be increased with light dose. Here, we reverse the process by thermal cycling.

The low-field SdH line shape was fitted using the best recursive fit[10] (BRF) in order to determine the SdH frequency F, and the Dingle temperature. Since the fitting routine requires fewer parameters when the line shape is a simple damped sinusoid as in the low-field region, the high-field limit for the fit was chosen to be below the field value where quantization of the Hall plateau and the zero resistance state were observed for the highest mobility condition. In the inset of Fig. 1 we have shown two representative data traces and the corresponding BRF's for high (a) and low (b) mobility data. The exponential decay of the SdH amplitudes determines T_D. Notice that SdH oscillations are observed to lower fields when the Dingle temperature is lower.

In Fig. 1, we have also plotted the Dingle temperature as a function of the carrier density. The Dingle temperature also increases as the carrier density decreases with thermal cycling although for the same variation in N_s the change is a factor of 8 compared to a change in T_μ of only about a factor of 2. This result suggests that the ratio T_D/T_μ varies with N_s; such an effect could originate from either of the following two mechanisms: First the sample may be more inhomogeneous for low values of N_s and thus phase cancellation of the SdH signals from different parts of the sample may produce an apparently larger T_D. We have investigated this effect by studying the current dependence of T_D and found it to be negligible (5–10%) effect at the low currents use in our experiments.

A second possible mechanism is increased small-angle scattering with decreasing N_s which produces an increase in the ratio T_D/T_μ. Das Sarma and Stern[3] (DS-S) have calculated the ratio τ_t/τ_s as a function of the carrier density for an ideal two-dimensional electron gas (2D EG) system with different values for the separation z, between the two-dimensional electron layer and the impurity layer. In Fig. 2, we have plotted the experimentally measured ratio $T_D/T_\mu = \tau_t/\tau_s$ as a function of k_F/q_{TF}, where $k_F = (2\pi N_s)^{1/2}$ is the Fermi wave vector and $q_{\text{TF}} = 2m^* e^2/\kappa\hbar^2 = 2\times10^6$ cm^{-1} is the Thomas-Fermi screening constant for GaAs. Also shown in the figure are the relevant theoretical curves of DS-S. Clearly, a comparison of theory and experiment shows a large discrepancy; the experimentally measured ratio τ_t/τ_s decreases with k_F/q_{TF} while theory predicts just the opposite behavior.

The discrepancy can be resolved through a closer examination of theory and experiment. In the DS-S calculation, the carrier density or k_F/q_{TF} is increased for a fixed spacer thickness by increasing the doping level in the impurity layer. They assume that the 2D EG density increases because the shallow donors in the impurity layer are depleted of their electrons and thus every electron that enters the 2D EG leaves behind a charged center that can cause scattering. The long-range Coulomb interaction due to the increase in the remote charged center density produces mostly small-angle scattering and hence, the ratio τ_t/τ_s increases with k_F/q_{TF} for a fixed spacer thickness according to their calculation.

We have observed, however, that the carrier density is reduced by thermal cycling after illumination of the sample by a light pulse at low temperatures. The persistent photoconductivity (PPC) effect in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ has been attributed to deep centers associated with large lattice relaxation by Lang, Logan, and Jaros (LLJ).[11,12] In n-type $\text{Al}_x\text{Ga}_{1-x}\text{As}$, these defects are denoted DX centers indicating that it is a complex defect consisting of a donor (D) and some unknown quantity (X). LLJ originally suggested that X is a vacancy in the As site[12] and were supported by the results of Narayanamurthi, Logan, and Chin.[13] Van Vechten and Wager[14] have suggested that the large lattice relaxation is vacancy nearest-neighbor hopping. The nearest-neighbor hopping would allow an As vacancy to hop to a nearby Ga site and also produce a Ga-on-As-site antisite defect:

$$V_{\text{As}} \longleftrightarrow V_{\text{Ga}} + \text{Ga}_{\text{As}} \; . \tag{4}$$

It has been suggested that As vacancies have a deep donor level while Ga vacancies have a deep acceptor level and the antisite (Ga_{As}) defect has one deep and one shallow acceptor level.[14,15] Thus, the reaction associated with the PPC effect in n-type $\text{Al}_x\text{Ga}_{1-x}\text{As}$ is[16]

$$D^+ V_{\text{Ga}}^- \text{Ga}_{\text{As}}^{2-} \longleftrightarrow D^+ V_{\text{As}}^0 + 3e^- \tag{5}$$

while for intrinsic AsGaAs (Ref. 16) it is

$$V_{\text{Ga}}^0 \text{Ga}_{\text{As}}^- \longleftrightarrow V_{\text{As}}^0 + e^- \; . \tag{6}$$

In both cases, light frees electrons and also reduces the charge state of the defect by one. In contrast, the charge state of a shallow silicon donor is increased by one when an electron is freed from the donor.

Our data (Fig. 2) indicate that the small-angle scattering decreases with increasing carrier density. This suggests that the deep centers responsible for PPC effect act

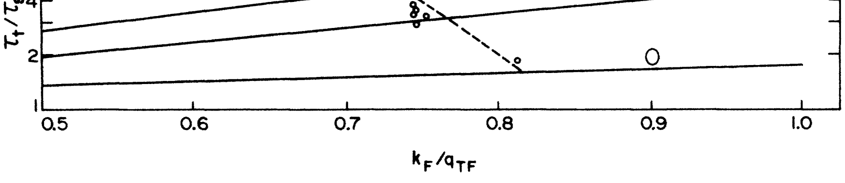

FIG. 2. Shown in the figure are the experimentally measured transport to single-particle lifetime ratios as a function of the normalized Fermi wave vector and the theoretical curves of Das Sarma and Stern.

as acceptors since when they are depleted (high N_s) there are fewer charged centers producing long-range Coulomb scattering so there is less small-angle scattering (low τ_t/τ_s). Therefore, our data appear to confirm the reactions[16] predicted for the PPC effect and also suggest the solution to the discrepancy between the calculation of DS-S and our experimental results. That is, DS-S did not include scattering from deep centers in their calculation.

In real GaAs/Al$_x$Ga$_{1-x}$As samples, the bulk of the scattering is caused by the deep centers which produce the PPC effect. This is apparent from the large discrepancy between data and calculation when the calculation only accounts for shallow donors. The deep defects show opposite behavior when compared to the shallow donors in that when an electron is removed from a shallow donor, the charge state increases while for the deep center the charge state decreases when electrons are freed. A complete calculation of the transport to single-particle lifetime ratio as a function of density would also include these acceptor *DX* centers.

In conclusion, we have shown that the Fermi wave-vector dependence of the transport to single-particle lifetime ratio does not agree with theory when the calculation takes into account only the shallow donors in the impurity layer. By correlating this result with models for the PPC effect, we have determined that the bulk of the small-angle scattering in real systems is caused by charged centers associated with deep defects responsible for the PPC effect. In addition, we have found that day-to-day variations of sample properties in the QHE regime caused by thermal cycling are due to the metastability of these defect states.

The sample used in this study was provided to us by Mr. R. Wilson. We acknowledge many useful discussions with Dr. J. K. Jain. This research was supported in part by the Defense Advanced Research Projects Agency (DARPA) under Grant No. DAAG29-85-K-0052.

---

[1] For a comprehensive review, see *The Quantum Hall Effect*, edited by R. E. Prange and S. M. Girvin (Springer-Verlag, New York, 1987).

[2] R. S. Háug, K. V. Klitzing, and R. Ploog, Phys. Rev. B **35**, 5933 (1987), and references therein; L. Bliek, E. Braun, G. Hein, V. Kose, J. Niemeyer, G. Weimann, and W. Schlapp, Semicond. Sci. Technol. **1**, 110 (1986), and references therein.

[3] S. Das Sarma and F. Stern, Phys. Rev. B **32**, 8442 (1985).

[4] R. B. Dingle, Proc. R. Soc. London, Sect. A **211**, 517 (1952).

[5] T. Ando, J. Phys. Soc. Jpn. **37**, 1233 (1974).

[6] T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 437 (1982).

[7] J. P. Harrang, R. J. Higgins, R. K. Goodall, P. R. Jay, M. Laviron, and P. Delescluse, Phys. Rev. B **32**, 8126 (1985).

[8] K. P. Martin, R. J. Higgins, J. J. L. Rascol, H. Yoo, and J. R. Arthur, in Proceedings of the 7th International Conference on Electronic Properties of Two-Dimensional Systems, p. 646; F. F. Fang, T. P. Smith, and S. L. Wright, *ibid*, p. 262.

[9] M. A. Hopkins, R. J. Nicholas, M. A. Brummel, J. J. Harris, and C. T. Foxon (private communication).

[10] J. R. Anderson, P. Heimann, W. Bauer, R. Schipper, and D. R. Stone, in *International Conference on the Physics of Transition Metals, Toronto, 1977*, edited by M. J. G. Lee, J. M. Perz, and E. Fawcett, Institute of Physics Conference Series, Vol. 39 (IOP, Bristol, 1978), p. 81.

[11] D. V. Lang, in *Deep Centers in Semiconductors*, edited by S. T. Pantelides (Gordon and Breach, New York, 1986), p. 489.

[12] D. V. Lang and R. A. Logan, Phys. Rev. Lett. **39**, 635 (1977); D. V. Lang, R. A. Logan, and M. Jaros, Phys. Rev. B **19**, 1015 (1979).

[13] V. Narayanamurthi, R. A. Logan, and M. A. Chin, Phys. Rev. Lett. **43**, 1536 (1979).

[14] J. A. Van Vechten, in *Microscopic Identification of Electronic Defects in Semiconductors*, edited by N. M. Johnson, S. G. Bishop, and G. D. Watkins, Materials Research Society Symposia Proceedings, Vol. 46 (MRS, Pittsburgh, 1985), p. 83; J. Phys. C **17**, L983 (1984); J. A. Van Vechten and J. F. Wager, J. Appl. Phys. **57**, 1956 (1985); J. F. Wager and J. A. Van Vechten, Phys. Rev. B **32**, 5251 (1985).

[15] G. A. Baraff and M. Schluter, Phys. Rev. Lett. **55**, 2340 (1985).

[16] R. J. Higgins, K. P. Martin, D. A. Syphers, J. A. Van Vechten, and S. C. Palmateer, Phys. Rev. B **36**, 2707 (1987).