

Electronic Dephasing in the Quantum Hall Regime

N. A. Fromer, C. Schüller,* and D. S. Chemla

*Department of Physics, University of California at Berkeley, Berkeley, California 94720
and Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720*

T. V. Shahbazyan and I. E. Perakis

Department of Physics and Astronomy, Vanderbilt University, Nashville, Tennessee 37235

K. Maranowski and A. C. Gossard

*Department of Electrical and Computer Engineering, University of California at Santa Barbara, Santa Barbara, California 93106
(Received 20 August 1999)*

By means of degenerate four-wave mixing (FWM), we investigate the quantum coherence of electron-hole pairs in the presence of a two-dimensional electron gas in modulation-doped GaAs-AlGaAs quantum wells in the quantum Hall effect regime. With increasing magnetic field, we observe a crossover from Markovian to non-Markovian behavior, as well as large jumps in the decay time of the FWM signal at even Landau level filling factors. The main observations can be qualitatively reproduced by a model which takes into account scattering by the collective excitations of the two-dimensional electron gas.

PACS numbers: 78.47.+p, 42.50.Md, 73.20.Dx, 78.66.Fd

The two-dimensional electron gas (2DEG) in modulation-doped semiconductor quantum systems is a subject of great and still growing interest since it allows, in specially tailored systems, the investigation of fundamental properties of electrons in reduced dimensions. In particular, in a strong magnetic field, 2D electrons form a strongly correlated system that exhibits such unique electronic transport properties as the integer and fractional quantum Hall effect. Linear optical experiments were successfully used to highlight these regimes of the 2DEG [1]. However, very little is known about the dynamics of such strongly correlated electron systems. On the other hand, ultrafast time resolved nonlinear spectroscopy (TRNS) provides unique and powerful tools for studying the dynamics of Coulomb correlation effects in semiconductors. Because the time resolution now reached is much shorter than the scattering times of elementary excitations and the period of phonons or plasmons, TRNS is well suited to investigate processes that are much more difficult to access through transport measurements, such as dephasing and dissipation [2]. In fact, it was demonstrated through TRNS that in undoped semiconductors both coherent and dissipative processes are governed by many-body effects [3]. Recently, four-particle and higher-order Coulomb correlation effects, which could not be explained within the time-dependent Hartree-Fock approximation (HFA), have been observed [4]. Compared to the wealth of experiments on intrinsic systems, rather few investigations of coherent dynamics in modulation-doped quantum wells, which contain a cold 2DEG, have been reported [5].

In this paper we investigate the quantum coherence of the interband polarization in the presence of a 2DEG in a multiple modulation-doped GaAs-AlGaAs quantum well

structure in the regime of the quantum Hall effect. We observe very strong variation of the interband dephasing time, T_2 , as a function of the filling factor, as well as direct evidence of memory effects in the optical dynamics. In a strong magnetic field, such that the 2DEG occupies only the lowest Landau level (LLL), there are no interactions between the photoexcited pairs, unless there is an asymmetry between electron and hole wave functions [6]. When the LLL is partially filled, the dephasing originates mainly from the scattering of the photoexcited carriers with the intra-LL collective excitations of the strongly correlated 2DE liquid [7–9]. We present a model based on magnetorotons that accounts for most of the observed effects.

We first present the experimental results and then discuss their interpretation. The samples are multiple period, modulation-doped quantum wells, antireflection coated and mounted on sapphire substrates for transmission measurements. We performed measurements on two samples whose active regions have thirty periods, each consisting of a 12 nm GaAs well and a 42 nm AlGaAs barrier, where the center 12 nm is doped with Si. The doped carrier density, n , under illumination is $n = 2.6 \times 10^{11} \text{ cm}^{-2}$ in sample A, and $n = 4.9 \times 10^{11} \text{ cm}^{-2}$ in sample B. Both samples had low temperature mobilities of $\mu \approx 8 \times 10^4 \text{ cm}^2/\text{Vs}$. They were immersed in superfluid helium in an optical split-coil cryostat at a temperature of 1.8 K. The four-wave mixing (FWM) [10] experiments were performed with two laser beams of equal intensity which were in resonance with transitions from valence-band to conduction-band LL. We used spectrally narrow $\tau = 300 \text{ fs}$ laser pulses to resonantly excite only one LL in strong magnetic fields. The excitation intensity was kept low enough for the density of photogenerated

e - h pairs, n_{eh} , to remain small compared to the doping density of electrons, typically $n_{eh} \lesssim n/10$. The beams were either left (σ^-) or right (σ^+) circularly polarized and separated by a time delay Δt . At $B = 0$, the linear absorption spectra, $\alpha(\omega)$, exhibit a clear Fermi edge, at $E \approx 1.545$ eV in A and at $E \approx 1.55$ eV in B. Only the LLL is occupied ($\nu < 2$), for $B > 5.1$ T in A and for $B > 9.8$ T in B. In time integrated (TI-FWM) experiments, the total signal intensity was measured by a photomultiplier tube, while for spectrally resolved experiments (SR-FWM) a spectrometer with 0.75 m focal length and a CCD camera were used to record the spectrum of the emitted signal.

Typical measurements of the TI-FWM signal, $S_{TI}(\Delta t)$, in sample A are shown in Fig. 1, for $B = 5.5 \rightarrow 11.5$ T using σ^+ polarized light (the σ^- data shows the same behavior). In these experiments the pulses were tuned to excite electrons only into the highest partially occupied LL, which contains the Fermi energy, E_F . For $5.5 \text{ T} \leq B \leq 6.5 \text{ T}$ the $S_{TI}(\Delta t)$ profile is a single exponential with an unusually long decay time. For $B \geq 7.5 \text{ T}$ the profile is more complicated, showing nonexponential behavior for short time delays. By extracting an overall decay time we can get a direct measure of the interband polarization dephasing time T_2 . The results are displayed by the open circles in the upper panel of Fig. 2 for sample A and in the lower panel for sample B. It is striking to note the very large jump of T_2 each time the system passes through even filling factors and, in particular, at $\nu = 2$. Since these features are reproducible as a function of ν for samples

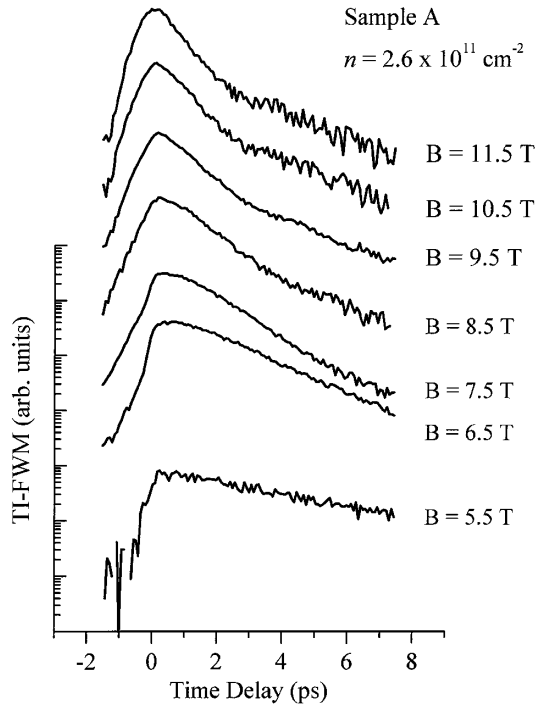


FIG. 1. TI-FWM signal measured in sample A using σ^+ polarized light for $B = 5.5 \rightarrow 11.5$ T.

with different densities, we can assert that this is an effect of the cold 2DEG.

The nonexponential behavior of the TI-FWM signal at high field is characterized by a change of slope that occurs in sample A at $\Delta t \approx 4.2 \rightarrow 2.5$ ps as $B \approx 7.5 \rightarrow 11.5$ T, indicating memory effects in the polarization dynamics. These are also seen in the frequency domain in Fig. 3, where we display the SR-FWM signal, $S_{SR}(\Delta t, \omega)$ [together with $\alpha(\omega)$], at fixed $\Delta t = 0$ for $B = 5.5 \rightarrow 11.5$ T in Fig. 3(a), and at fixed $B = 11$ T for $\Delta t = 0 \rightarrow 6$ ps in Fig. 3(b). Clearly, the $S_{SR}(\omega)$ profile changes from a Lorentzian line shape with a constant width, $\Gamma \propto T_2^{-1}$, to an asymmetric one that would correspond to a frequency-dependent width, $\Gamma(\omega)$. In Fig. 3(a) this occurs for $B \geq 7.5$ T, and in Fig. 3(b) for $\Delta t \lesssim 3$ ps. Such a profile indicates a polarization relaxation term $\propto \Gamma(\omega)P(\omega)$, which gives, in the time domain, a dephasing with memory structure, i.e.,

$$\frac{\partial P}{\partial t} \Big|_{\text{scatt}} = \int_{-\infty}^t dt' \Gamma(t - t') P(t'). \quad (1)$$

We note also that, if the $S_{SR}(\omega)$ spectra are asymmetric, they are redshifted from the $\alpha(\omega)$, while if they are Lorentzian they almost coincide with the $\alpha(\omega)$ peaks.

The scattering rates for the density matrix elements, $\hat{\rho}$, i.e., interband polarization and occupation numbers, can be calculated using the general nonequilibrium formalism [11]. The memory kernel within the LLL can be

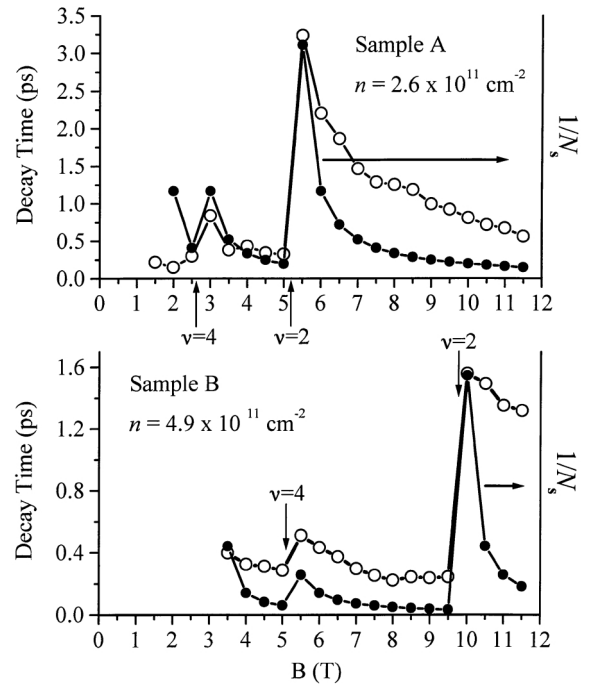


FIG. 2. TI-FWM decay times versus magnetic field for samples A and B. The open circles are the experimental data points, and the filled circles correspond to $N_s^{-1} = \nu/[2(N + 1) - \nu]$, where N is the LL number and ν is the filling factor. The data was taken using σ^+ polarized light.

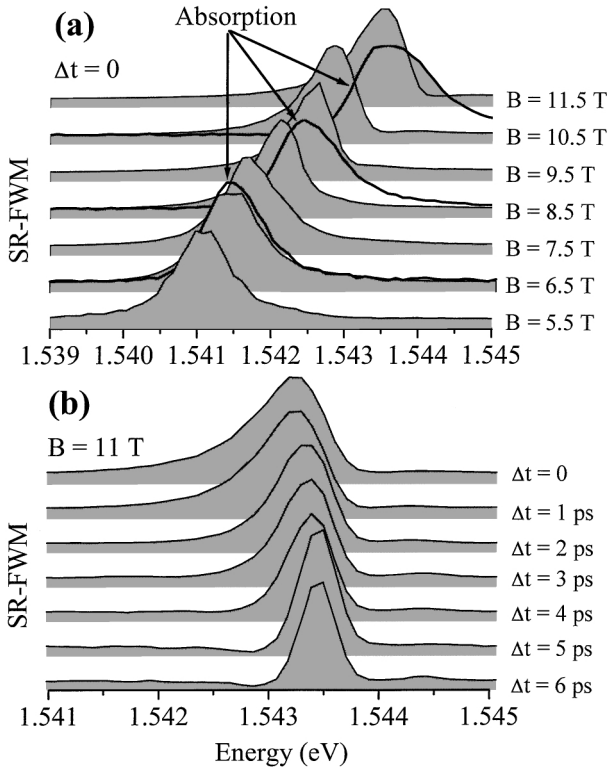


FIG. 3. Gray shaded curves: SR-FWM signal at (a) fixed $\Delta t = 0$ for $B = 5.5 \rightarrow 11.5$ T and at (b) $B = 11$ T for $\Delta t = 0 \rightarrow 6$ ps. The thick, unshaded lines in (a) show the linear absorption spectra, $\alpha(\omega, B)$, for $B = 6.5, 8.5,$ and 10.5 T.

presented as $\Gamma(t - t') = (2\nu^{-1} - 1)\kappa(t - t')$, where the factor $(2\nu^{-1} - 1)$, expected on general physical grounds, is proportional to N_s , the number of empty states available for scattering within the LL containing E_F . It has the form $N_s \propto [2(N + 1) - \nu]/\nu$ in the N th LL (factor of 2 for the spin). In addition to scattering with the intra-LL collective excitations, there are several inter-LL relaxation processes which contribute to the dephasing at weaker fields, e.g., phonon and impurity scattering, Auger-like processes, etc. [12]. These background processes lead to Markovian dephasing, $\kappa(t) \rightarrow \delta(t)$, with $T_{2,bg} = [N_s F(B)]^{-1}$, where $F(B)$ depends only weakly on B (mainly via inhomogeneous LL broadening). We have plotted N_s^{-1} in Fig. 2 (filled circles), normalized so that the maximum height coincides with that of the T_2 curve. For low fields the agreement is striking; however, there are significant differences in the B dependence of T_2 for strong field. In particular, the change in behavior occurs for sample A at $B \gtrsim 7.5$ T, where we begin to see the nonexponential behavior in Fig. 1, or the asymmetry in Fig. 3(a). Also, above this field, the dephasing rate in Fig. 2 begins to differ considerably from N_s^{-1} . Our analysis of the experimental data to get the decay times of Fig. 2 is equivalent to a Markovian approximation of Eq. (1). We attribute this observed transition from

Markovian to non-Markovian behavior to a suppression of the inter-LL scattering relative to the dynamical response of the collective excitations of the 2DE liquid. At large magnetic fields, where the cyclotron energy $\hbar\omega_c$ is large compared to other characteristic energies of the system, relaxation is dominated by intra-LL processes. Scattering by collective excitations involves the matrix elements of the dynamically screened interaction, $U_{ij}^<(t, t')$, which in the LLL have the form

$$U_{ij}^<(t, t') = \int \frac{d\mathbf{q}}{(2\pi)^2} e^{-q^2 l^2/2} v_q^2 \bar{\chi}_q^<(t, t') c_{ij}(q), \quad (2)$$

where $\bar{\chi}_q^<(t, t') = \langle \bar{\rho}_{\mathbf{q}}(t') \bar{\rho}_{-\mathbf{q}}(t) \rangle$ is the density-density correlation function projected onto the LLL [7,8], and $\bar{\rho}_{\mathbf{q}}(t)$ is the corresponding density operator. Also, v_q is the unscreened Coulomb interaction, $l = (\hbar/eB)^{1/2}$ is the magnetic length, and the $c_{ij}(q)$ with $i, j \rightarrow e, h$ model the asymmetry in the $e-e$ and $e-h$ interaction matrix elements, which originates from the difference between electron and hole LLL wave functions. Because of the breakdown of the perturbation theory due to LL degeneracy in 2D systems at high fields, it is incorrect to evaluate $\bar{\chi}_q^<(t, t')$ within the standard random-phase approximation [11]. Instead, one should account for the true excitations of the interacting 2DE liquid. Several models can be found in the literature, and we base our discussion on the magnetoroton model, which is the one best suited for our filling factors. The most salient features are, however, general and model independent. The magnetoroton dephasing mechanism is somewhat similar to that of acoustic phonon scattering. The details are presented elsewhere [13], but we discuss here the general trends. In our experimental conditions, to a very good approximation, the intra-LL collective excitations are not affected by the small density of photogenerated carriers, so one can use the equilibrium density correlation function [7], and

$$\begin{aligned} \left. \frac{\partial \hat{\rho}_{ij}}{\partial t} \right|_{\text{scatt}} &= i \sum_k \int_{-\infty}^t dt' G_i^r(t - t') G_j^a(t' - t) \\ &\times \{ [U_{ik}^<(t - t') - U_{kj}^<(t - t')] \rho_{ik}^<(t') \rho_{kj}^>(t') \\ &- (< \leftrightarrow >) \}, \end{aligned} \quad (3)$$

where $G_i^{r/a}(t)$ is the retarded/advanced Green function, $\rho_{ij}^< = \rho_{ij}$, and $\rho_{ij}^> = \delta_{ij} - \rho_{ij}$. If all U_{ij} are equal, i.e., $c_{ij}(q) = 1$, then the polarization scattering term vanishes [6]. This corresponds to identical electron and hole wave functions in the LLL. In practice, there is always asymmetry between electrons and holes, due to, e.g., differing band offsets, lateral confinement, and disorder. Using the results of Ref. [7], Eq. (2) takes the form

$$\begin{aligned} U^<(t) &= -\frac{in}{2\pi} \int \frac{d\mathbf{q}}{(2\pi)^2} e^{-q^2 l^2/2} v_q^2 c_{ij}(q) \\ &\times \bar{s}_q [(N_q + 1)e^{i\omega_q t} + N_q e^{-i\omega_q t}], \end{aligned} \quad (4)$$

where N_q is the Bose distribution function for magnetorotons of energy ω_q , and \bar{s}_q is the static structure factor of the 2DE liquid in the LLL. By comparing Eqs. (3) and (1), we see that the ω dependence of $\Gamma(\omega)$ is determined by the Fourier transform of $U^<(t)$, which is governed by the q dependence of \bar{s}_q . In the LLL, $\bar{s}_q = (2\nu^{-1} - 1)\tilde{s}_q$ [14], where $\tilde{s}_q \sim (ql)^4$ for $ql \ll 1$, $\sim \exp(-q^2l^2/2)$ for $ql \gg 1$, and \tilde{s}_q displays a peak for $ql \sim 1$ [7] that leads to the magnetoroton excitations. The corresponding resonance in $\Gamma(\omega)$ near the magnetoroton energy leads to non-Markovian behavior with a characteristic response time of approximately the inverse of this energy. The latter is estimated from the gap at the magnetoroton dispersion minimum, $\Delta \sim 0.1(e^2/\epsilon l)$ for our range of ν [7], which for $B = 10$ T is ≈ 1.5 meV. The experimental data of Figs. 1 and 3 strongly support our interpretation, since they imply a reaction time $T_r \approx 2.5 \rightarrow 4$ ps for the 2DE-liquid collective excitations. We note that this corresponds to an energy $\approx 1 \rightarrow 2$ meV. Clearly, a much more involved theoretical treatment is needed to identify the details of the interaction processes in this regime [13].

The non-Markovian behavior of 2DEG excitations is well documented at zero field, where the ultrafast nonlinear response of a Fermi sea of electrons is determined by the continuum of e - h pairs excited by the Coulomb potential of the photoinduced carriers. The small characteristic energy of these excitations gives rise to a nonadiabatic Fermi sea response leading to a nonexponential polarization decay (absent in the HFA) [15]. We also see here (in Fig. 3) similar effects in the B - and Δt -dependent shifts of the SR-FWM signal. For large field, e.g., $B = 10.5$ T, $S_{SR}(\omega)$ is redshifted from the $\alpha(\omega)$ resonance due to a lowering of the 2DE-liquid energy by the attractive potential of a photoexcited hole, a process similar to that known for the Fermi edge singularity [16]. This dynamical redshift comes from the real part of the magnetoroton-induced self-energy. Since the latter is also proportional to N_s , the redshift is absent for nearly filled LLL, i.e., at $\nu \approx 2$ or $B \approx 5.5$ T (in sample A); the reason is that a 2DE liquid in an incompressible state cannot readjust to screen the hole potential.

In conclusion, we have investigated the quantum coherence of electron-hole pairs in multiple period, modulation-doped GaAs-AlGaAs quantum wells in the quantum Hall regime. We observe a clear transition from Markovian to non-Markovian behavior with increasing magnetic field. In the former case, the dephasing is dominated by inter-LL electron relaxation, and the B dependence of the dephasing time follows that of the number of available scattering states exhibiting peaks at even Landau level filling factors. At high magnetic field, the FWM signal shows strong evidence of memory effects. We proposed a model based on scattering of the photoexcited electrons with magne-

toroton excitations in the lowest Landau level that qualitatively accounts for the main features of the experimental observations.

The authors are grateful to Lu Sham and Ming Wei Wu for very helpful discussions. This work was supported by the Alexander von Humboldt-Stiftung (C.S.) and by the Director, Office of Energy Research, Office of Basic Energy Sciences, Division of Material Sciences of the U.S. Department of Energy, under Contract No. DE-AC03-76SF00098. T. V. S. and I. E. P. were supported by NSF Grant No. ECS-9703453 and by Hitachi, Ltd.

*On leave from: Institut für Angewandte Physik und Zentrum für Mikrostrukturforschung, Jungiusstr. 11, 20355 Hamburg, Germany.

- [1] See, e.g., I. V. Kukushkin *et al.*, Phys. Rev. Lett. **72**, 736 (1994); B. B. Goldberg *et al.*, Phys. Rev. Lett. **65**, 641 (1990); A. J. Turberfield *et al.*, Phys. Rev. Lett. **65**, 637 (1990); E. H. Aifer *et al.*, Phys. Rev. Lett. **76**, 680 (1996).
- [2] J. Eisenstein *et al.*, Phys. Rev. Lett. **69**, 3804 (1992).
- [3] For a recent review, see D. S. Chemla, in *Nonlinear Optics in Semiconductors*, edited by R. K. Willardson and A. C. Beers (Academic Press, New York 1999).
- [4] P. Kner *et al.*, Phys. Rev. Lett. **78**, 1319 (1997); Phys. Status Solidi (a) **164**, 579 (1997); P. Kner *et al.*, Phys. Rev. Lett. **81**, 5386 (1998); Phys. Rev. B **60**, 4731 (1999); G. Bartels *et al.*, Phys. Rev. Lett. **81**, 5880 (1998); B. Haase *et al.*, Phys. Rev. B **59**, R7805 (1999); A. Schülzgen *et al.*, Phys. Rev. Lett. **82**, 2346 (1999); T. Aoki *et al.*, Phys. Rev. Lett. **82**, 3108 (1999).
- [5] W. H. Knox *et al.*, Phys. Rev. Lett. **61**, 1290 (1988); D. S. Kim *et al.*, Phys. Rev. Lett. **68**, 2838 (1992); P. Hawrylak *et al.*, Semicond. Sci. Technol. **9**, 432 (1994); S. Bar-Ad *et al.*, Phys. Rev. Lett. **72**, 776 (1994); I. E. Perakis, Chem. Phys. **210**, 259 (1996).
- [6] I. V. Lerner and Yu. E. Lozovik, Zh. Exp. Teor. Fiz. **80**, 1488 (1981) [Sov. Phys. JETP **53**, 763 (1981)].
- [7] S. Girvin *et al.*, Phys. Rev. B **33**, 2481 (1986).
- [8] R. Haussmann, Phys. Rev. B **53**, 7357 (1996).
- [9] A. Pinczuk *et al.*, Phys. Rev. Lett. **70**, 3983 (1993).
- [10] For experimental details and notations, see Ref. [3].
- [11] H. Haug and A.-P. Jauho, *Quantum Kinetics in Transport and Optics of Semiconductors* (Springer, Berlin, 1996), and references therein.
- [12] M. Potemski *et al.*, Phys. Rev. Lett. **66**, 2239 (1991); T. A. Vaughan *et al.*, Phys. Rev. B **53**, 16481 (1996).
- [13] T. V. Shahbazyan *et al.* (to be published).
- [14] Here we follow Ref. [7], but we include a factor of 2 since we neglect spin splitting in the calculations.
- [15] I. E. Perakis and D. S. Chemla, Phys. Rev. Lett. **72**, 3202 (1994); I. E. Perakis *et al.*, J. Opt. Soc. Am. B **13**, 1313 (1996); T. V. Shahbazyan *et al.* (to be published); N. Primožich *et al.* (to be published).
- [16] I. E. Perakis and Yia-Chung Chang, Phys. Rev. B **44**, 5877 (1991); **43**, 12556 (1991); **47**, 6573 (1993).