Carrier-Carrier Scattering in a Degenerate Electron System: Strong Inhibition of Scattering near the Fermi Edge

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(Received 29 January 1992)

We report the first direct measurement of carrier-carrier scattering rates in a degenerate electron system. Our results on modulation-doped quantum wells, using femtosecond four-wave-mixing (FWM) techniques, demonstrate a strong inhibition of scattering near the Fermi edge, and exhibit other behavior predicted by Landau Fermi liquid theory. Time-resolved (100 fs) FWM measurements clearly show photon echoes, demonstrating the inhomogeneous character of this intrinsic system, as well as prompt signals arising from many-body effects.

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

Electrons in metals, semimetals, and degenerate semiconductors can be regarded as a quantum Fermi liquid [1], in which an important role is played by both the Pauli exclusion principle and by the interaction between the quasiparticles. As striking physical consequences of the exclusion principle, the specific heat of an electron gas becomes proportional to temperature instead of being constant, and the spin susceptibility becomes temperature independent instead of varying inversely with temperature. As a consequence of the interaction between the quasiparticles, the resistance of a metal increases as the square of the temperature. Although these and many other aspects of Landau Fermi liquid theory have been verified, there have been no *direct* measurements of the quasiparticle interaction rate in a degenerate electron liquid.

Carrier-carrier scattering also plays a crucial role in many aspects of semiconductor physics and devices, and has been investigated using various optical techniques. In undoped semiconductors, carrier relaxation processes have been investigated using femtosecond pump-and-probe spectroscopy in bulk [2] and quantum wells [3], polarization rotation spectroscopy in bulk [4] and quantum wells [5], and femtosecond luminescence spectroscopy in bulk [6]. Dephasing of carriers in undoped bulk [7] and quantum wells [8] has been investigated using four-wave-mixing (FWM) techniques with ≤ 10-fs pulses. In modulation-doped quantum wells, electron-hole scattering, and the resulting negative mobility, have been studied using cw luminescence imaging techniques [9], and energy relaxation rates as a function of excess energy have been investigated at room temperature using femtosecond pump-and-probe techniques [10].

Modulation-doped quantum wells provide an ideal system for optical investigations of carrier-carrier scattering in semiconductors because atomic excitons are destabilized by the high-mobility quasi-2D carrier gas. Such a system at low temperatures is a degenerate Fermi liquid in which the Fermi energy can be varied without changing other parameters. Furthermore, the high-density (weak coupling) limit in which r_s, the interparticle distance expressed in units of exciton Bohr radius, is ≤ 1 can be easily achieved. Such a system is, therefore, ideal for measuring carrier scattering rates near the Fermi energy and comparing them with the predictions of Landau Fermi liquid theory.

In this Letter, we report the first *direct* measurement of carrier dephasing rates in a degenerate electron system. The measurements were made using femtosecond time-integrated and time-resolved FWM spectroscopy of high-quality modulation-doped quantum wells over a wide range of photon energy, temperature, and density. Our results show a strong inhibition of carrier scattering rates near the Fermi energy, with dephasing times as long as 40 ps. These quickly reduce to ≤ 400 fs as the incident photon energy is increased above the Fermi edge. The dephasing rate varies roughly as the square of the electron excess energy with a scale set by the Fermi energy, in agreement with Landau Fermi liquid theory. The results also show that the hole dephasing times are several tens of picoseconds. These results represent the first definitive measurement of carrier dephasing rates in semiconductors. In addition to these FWM measurements in which the time-integrated FWM signal is measured, we also report measurements of the *time-resolved* FWM signal with 100-fs time resolution [11]. The results clearly show photon echoes and thereby demonstrate that the excited electron-hole states have an inhomogeneous character in momentum space in this *intrinsic system.*

The experiments were performed on two n-modulation-doped GaAs/$Al_{0.3}Ga_{0.7}As$ quantum wells with 60 (100) periods, 80-Å (60-Å) wells, 100-Å barriers, and a nominal electron concentration of 2×10^{11} cm^{-2} (6×10^{11} cm^{-2}) corresponding to a Fermi energy of 7 meV (20 meV), for sample A (B). Two-pulse, time-resolved, self-

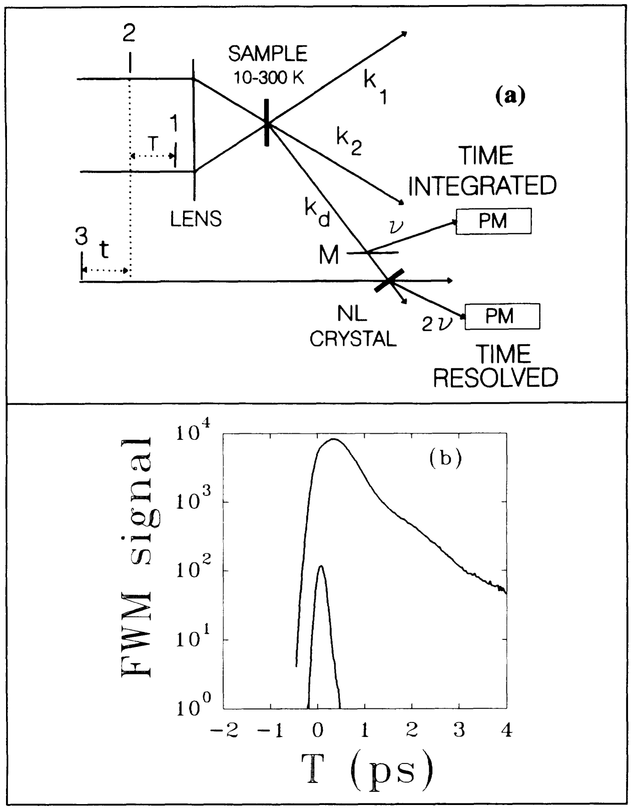

FIG. 1. (a) Schematic of the experimental configuration; M is a removable mirror and NL crystal is a $LiIO_3$ crystal. (b) TI-FWM signal vs time delay T for two different incident photon energies for sample A at 10 K. Long decay time (about 1 ps) is observed for $\delta E=0$ and very short decay time (<100 fs) is observed for $\delta E=12$ meV. The excitation density is 5.5×10^9 cm^{-2}.

diffracted, degenerate FWM experiments were performed using a self-mode-locked Ti:sapphire laser tunable from 720 to 880 nm. The pulse width was 100 fs (laser bandwidth 15 meV). In this form of FWM [Fig. 1(a)], two pulses propagating along $\mathbf{k}_1$ and $\mathbf{k}_2$ create a grating in the sample which diffracts the second pulse into the background-free direction $\mathbf{k}_d=2\mathbf{k}_2-\mathbf{k}_1$. The time-integrated FWM (TI-FWM) signal along $\mathbf{k}_d$ was measured over a wide range of time delays T (positive when pulse 1 precedes pulse 2), photon energy, and excitation density. In addition, the time-resolved FWM (TR-FWM) signal was detected with 100-fs time resolution by cross correlating the diffracted signal along $\mathbf{k}_d$ with a third laser beam which did not pass through the sample.

Figure 1(b) shows the TI-FWM signal versus time delay T for sample A at 10 K for two incident photon energies. We characterize the incident photon energy by δE, the energy separation of the center of the laser spectrum from the Fermi-edge-singularity peak in the photoluminescence excitation (PLE) spectrum. For $\delta E=0$, the signal decays slowly. However, for a small change in the incident photon energy ($\delta E=12$ meV), the signal decays with a time constant of ≤ 100 fs, limited by our time resolution. In addition, the maximum TI-FWM signal close to $T=0$ shows a strong (500:1) resonance with the photon energy (Fig. 2). The peak of the resonance coincides with the Fermi edge singularity in PLE spectra and the resonance shifts in both samples. The resonance begins to broaden when the thermal energy exceeds the Fermi energy.

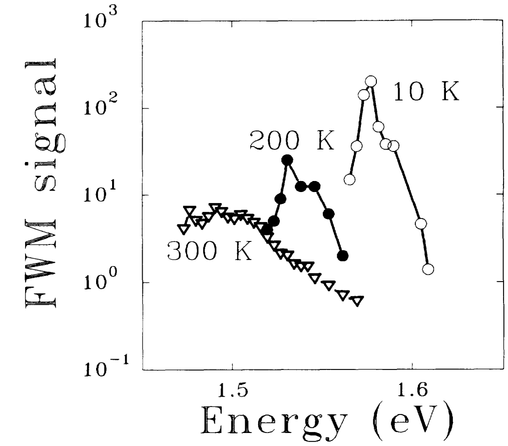

FIG. 2. Maximum TI-FWM signal vs incident photon energy for sample A at three temperatures.

For a given δE, we find that the decay rate of the TI-FWM signal varies linearly with the excitation density. Figure 3 shows the zero-density decay rate obtained by extrapolating such curves versus $\delta E/E_F$ for both samples, where E_F is the Fermi energy. The decay time τ ($=T_2/4$ where T_2 is the dephasing time) is as large as 10 ps for negative δE, but decreases very rapidly and becomes time-resolution limited at large δE. Note that the decay rate varies by nearly a factor of 100, with most of the variation occurring for laser energies above the Fermi edge. From a log-log plot (inset of Fig. 3) of $1/\tau$ vs $\delta E/E_F$ (for positive δE), we deduce that $1/\tau$ varies

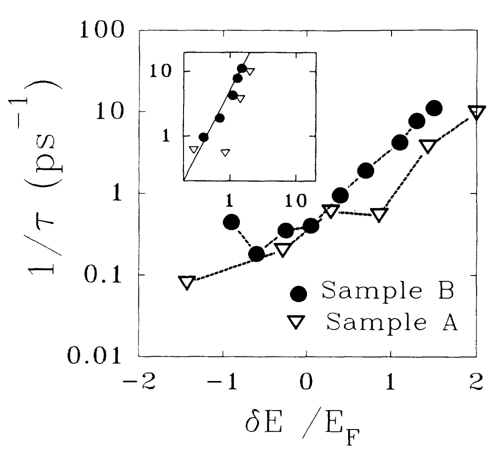

FIG. 3. Zero-density decay rate of TI-FWM signal vs $\delta E/E_F$ for sample A (open triangles) and sample B (solid circles). Inset: A log-log plot for positive δE, showing a nearly quadratic variation with $\delta E/E_F$.

roughly as the square of $\delta E/E_F$.

Figure 4 shows TR-FWM signals versus time t for sample B at various time delays T for circularly copolarized beams [12]. Time t is measured with respect to pulse 2. The data show a *single* peak that moves linearly with the time delay, a very clear signature of a photon echo. In contrast, the low-density sample A shows the photon echo signal plus a weak prompt signal (close to $t=0$) for small T for copolarized beams; for cross-polarized beams, the echo disappears and only this prompt signal is present as shown in the inset of Fig. 3 for $T=1$ ps. The position of this prompt signal is independent of T, but its strength decreases with increasing T.

These measurements of the dephasing of carriers are relevant not only to the particular semiconductor system investigated here, but also to a Fermi liquid in general. The data show that there is a large variation in the dephasing rates of the carriers near the Fermi energy and that inhibition of scattering near the Fermi energy leads to a dephasing time as long as 40 ps in the degenerate quasi-2D system studied.

We now present a detailed discussion of the results. The dephasing is determined by scattering of electrons as well as holes. However, the observed spectral resonance in the FWM signal and the associated sharp change in the dephasing rate coincide with the Fermi edge singularity in PLE, the temperature dependence is consistent with the broadening of the Fermi surface, and the data in Fig. 3 scale with the Fermi energy. Furthermore, the hole dephasing times are not expected to vary strongly with δE in the range investigated. *We, therefore, conclude that the observations are related to the properties of the degenerate electron system under investigation.* It follows that the hole dephasing times at low temperature are

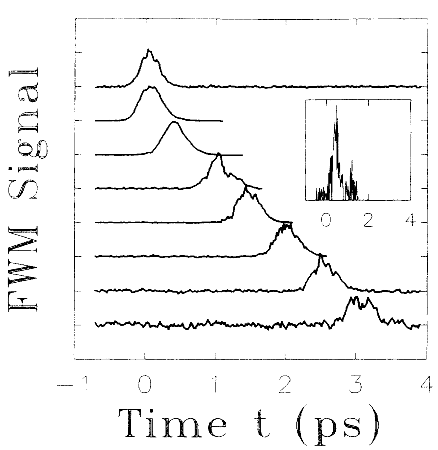

FIG. 4. TR-FWM signal for sample B at 10 K for copolarized circular beams (linear scale). The curves are normalized to the same height and displaced vertically for clarity. Time delay T is, from top to bottom, -0.2, 0, 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 ps. For the curve near zero time delay, the peak signal is nearly 1000 times the noise. Inset: TR-FWM signal (linear scale) from sample A at 10 K for cross-polarized circular beams vs time t in ps; time delay $T=1$ ps.

several tens of picoseconds.

The observed variation of the electron dephasing times with incident photon energy can be qualitatively explained as follows. Since the states below the Fermi energy are occupied at low temperatures, an electron with an energy ϵ above the Fermi energy can be scattered only by electrons within energy ϵ below the Fermi energy. Because of this limitation on the number of electrons available for scattering imposed by the Pauli exclusion principle, the dephasing rate increases as ϵ increases. The strong resonance in the FWM signal at the Fermi edge arises because states with the longest dephasing time always dominate and give the strongest FWM signals [13,14]. The temperature dependence is a result of the shift and smearing of the Fermi edge with temperature.

It is known from the theory of a degenerate Fermi liquid in quasi-2D systems that the scattering rate of electrons with excess energy ϵ varies as $x^2 \ln x$, where $x=\epsilon/E_F$ [15]. The observed behavior is qualitatively consistent with this expectation, i.e., the dephasing time becomes very long near the Fermi energy on a scale set by the Fermi energy. A quantitative comparison would require a calculation of the FWM signal, averaged appropriately over the entire spectral bandwidth of the laser, and taking into account this expected variation of the dephasing time with energy. Such a calculation is in progress but is beyond the scope of this Letter.

We now turn to a discussion of the *time-resolved* data. The data in Fig. 3 show a peak that occurs at $t=T$. This is a photon echo signal; its observation provides a direct demonstration that the continuum states in a semiconductor can indeed be considered as being inhomogeneously broadened in momentum space. This is an *intrinsically* inhomogeneously broadened system.

The appearance of an additional prompt peak in the TR-FWM signal at low doping concentrations (sample A) may be understood by noting that, with decreasing Fermi energy, the Fermi edge singularity transforms continuously into the usual atomic exciton [16]. In the absence of disorder and unlike continuum states, excitons are homogeneously broadened and thus should give rise to a prompt TR-FWM signal. For small doping concentrations (Fermi energy E_F smaller than or comparable to the exciton binding energy), strong excitonic effects persist, and simultaneous excitation of the Fermi edge singularity and higher-lying states should then lead to a TR-FWM signal with both prompt and photon echo components. Apart from different dephasing rates, the situation is thus similar to simultaneous excitation of unperturbed excitons and continuum states in an undoped quantum well [8,14]. In sample B, the Fermi energy is about 3 times the unperturbed exciton binding energy and no significant deviations from simple photon echo behavior are expected.

Furthermore, as discussed previously for undoped quantum wells [11,13,17–19], the FWM signal is also subject to strong many-body Coulomb effects. For the inhomogeneous case, such a process can alter the magnitude of the photon echo signal but not its temporal line shape [18,19], consistent with our observation in sample B. For the homogeneous case, the FWM efficiency is again enhanced and the FWM signal shows unusual temporal behavior. We believe that we see evidence for such behavior in sample A [20]. More detailed experimental and theoretical studies of the TR-FWM signal as a function of doping are in progress and will be discussed in a future publication.

In conclusion, we have made the first measurements of carrier scattering rates in a degenerate Fermi liquid. The measurements show a strong inhibition of electron scattering near the Fermi energy, with dephasing times as long as 40 ps. The hole scattering times are also greater than 40 ps. The electron dephasing rate varies approximately quadratically with excess energy on a scale set by the Fermi energy, as expected from Landau Fermi liquid theory. We have also presented time-resolved measurement of the four-wave-mixing signals with 100-fs time resolution. The photon echo observed in these measurements demonstrates the inhomogeneous nature of excited electron-hole states in momentum space and shows that this is an intrinsic inhomogeneously broadened system. At low doping concentrations, the time-resolved signal also shows an additional peak resulting from many-body interactions in the semiconductor. We expect that a detailed comparison with calculations will provide new insights into the coherent properties of semiconductors.

We thank E. P. Ippen and W. H. Knox for helpful discussions, and W. H. Knox for the loan of processed samples.

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