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Suppression of ground-state optical recombination in the quantum Hall regime

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The time evolution of optical recombination in the two-dimensional electron gas in GaAs/(Ga,Al)As heterostructures shows an anomalous increase at the Landau-level filling factor $\nu=1$. Here we find that the radiative recombination rate is slowed by an order of magnitude and is commensurate with the quantum Hall effect. The inhibited electron-hole recombination is caused by localization and changes in the screening response of the electron gas, which leads to reduced electron-hole overlap and broadening of the density of states. These mechanisms are also manifest in a large increase in hole relaxation time at $\nu=1$.

Optical measurements have recently emerged as a valuable method to study the integer and fractional quantum Hall effects (QHE).[1-5] In high mobility GaAs/$Ga_{1-x}Al_xAs$ samples ($\mu \sim 10^6$ cm^2/Vs) striking spectral features are observed in photoluminescence (PL) that are correlated to the Landau-level filling factor ν. These anomalies include characteristic minima in the emission intensity at the Landau-level filling factors $\nu=1$ and $\frac{2}{3}$, in addition to spectral redshifts and blueshifts and peak splittings.[3,4,6] It has also been observed that the minima in the ground-state PL at integer ν are accompanied by maxima in the excited-state emission.[3] Unfortunately with the cw photoluminescence used so far, it is difficult to determine the specific mechanism giving rise to the spectral anomalies. For example, it is not known whether intensity minima are caused by a reduced recombination rate or by an increase in nonradiative processes. On the other hand, time-resolved PL probes the radiative recombination time, which is a direct measure of the spatial overlap of electrons and holes and their densities of states. Knowledge of these processes is expected to give further insight into the underlying mechanisms of localization, screening, and many-body effects.

In this paper we describe the first time-resolved optical investigation of the two-dimensional (2D) electron gas in the quantum Hall regime. Using time-resolved PL, we find a large increase in the PL rise time and decay time at $\nu=1$. The anomaly disappears for temperatures $T>2$ K and $\nu\neq 1$. Using a simple phenomenological model for the PL kinetics shows that the ground-state recombination time is increased by as much as 7 times at the $\nu=1$ spin gap. The hole relaxation time in a quantum well shows an increase by a factor of 2. This is the first direct optical measurement of the influence of screening and localization, responsible for the QHE, on the radiative lifetime of holes. The increase in ground-state recombination time also accounts for the increase observed in the intensity from PL decay channels competing with the ground-state recombination.

Experiments were carried out on a GaAs/$Ga_{1-x}Al_xAs$, $x=0.3$, $L_z=40$ nm single quantum well (SQW) and a single interface (SI) both with n-type doping. The SQW was an asymmetric structure with single-side doping. For a well width of 40 nm this results in a situation very similar to the SI, i.e., the 2D electron gas is located on one side of the well. Time-resolved PL was obtained by time-correlated single-photon counting spectroscopy. A single optical fiber (core diameter 600 μm) was used for excitation and collection of the PL.[7] The light source was a pulsed diode laser at 20-MHz repetition rate with a center energy $E_L=1575$ meV, multimode emission having a 10-meV-wide envelope, 0.5-ns pulsewidth, and average power 1-50 μW. The full width at half maximum of the total system response was typically 600-700 ps. Deconvolution

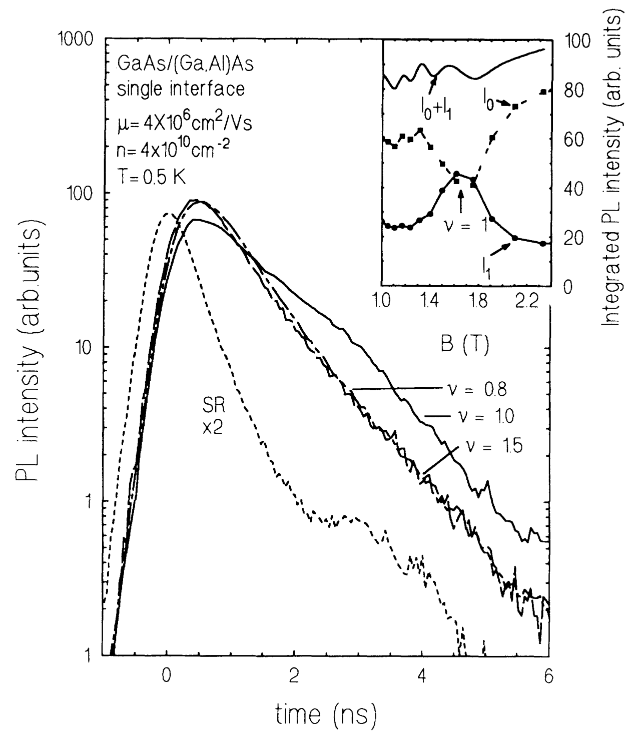

FIG. 1. The time-evolution of photoluminescence emission for a $GaAs/Ga_{1-x}Al_xAs$ single interface ($n=4.0\times10^{10}$ cm^{-2}, $\mu=4\times10^6$ cm^2/V s, and $x=0.3$) for three different Landau-level filling factors ν at $T=0.5$ K. The spectral energies correspond to the maxima of the time-integrated photoluminescence. All curves are normalized to equal integral intensity. A system response is also displayed by the dashed curve (SR). Inset: Integrated cw photoluminescence intensity for ground state, I_0 (■); first-excited state, I_1 (●); and the sum of the two.

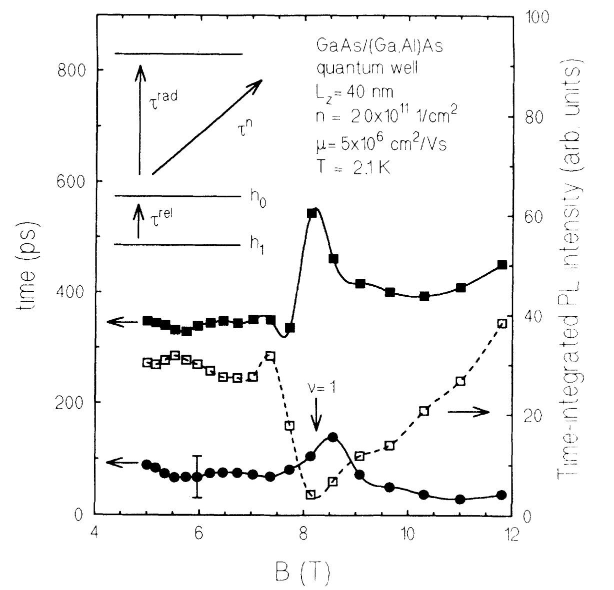

FIG. 2. Plot of the lifetimes τ_1(■) for the ground-state holes, $\tau^{\rm rel}$(●) for excited-state holes, and time-integrated photoluminescence intensity $\bar{I}$(□) in a $GaAs/Ga_{1-x}Al_xAs$ single quantum well with $n=2.0\times10^{11}$ cm^{-2}, $\mu=5\times10^6$ cm^2/V s, $x=0.3$, and well width $L_z=40$ nm. The curves are guides for the eye. Inset: Level scheme and decay channels for the two-level model used to analyze the data.

of the data by a Fourier-transform technique[8] resulted in a time resolution of approximately 70–100 ps. The accuracy of the derived rise and decay times, however, is more affected by the nonexponential behavior of the decay, which was even more pronounced at $\nu=1$.

Three time-evolution curves of the ground-state PL for a SI are shown in Fig. 1, along with the response of the measuring system. It is obvious that at Landau-level filling factor $\nu=1$ the decay time is significantly longer than for $\nu=1.5$ and $\nu=0.8$. A similar time evolution is observed for the SQW, however, the decay times are shorter due to the larger electron-hole overlap enforced by the well potential. The observed time evolution is governed by the kinetics of the minority carriers, in our case the photogenerated holes in the valence subbands.

In order to analyze the ground-state PL time evolution we adopt a simple two-level system[9] for the holes, as shown in the inset of Fig. 2. The hole level denoted h_0 refers to the ground state with regard to both subband confinement and Landau level, and h_1 represents the envelope of the excited states. Our model takes only three transitions into account, with three characteristic times. The excited level h_1 is initially populated and relaxes with a time $\tau^{\rm rel}$ into the ground state h_0. From h_0 a radiative recombination with a ground-state electron occurs with time $\tau^{\rm rad}$. We include all processes that remove a hole from the ground-state without producing ground-state luminescence by the "nonradiative" time τ''. These processes are dominated by recombinations with other nonground-state electrons as will be discussed later in connection with the recombination from the excited subband. We also assume that the number of electrons in the ground-state conduction subband is constant given the low intensity of the light pulses in our experiment. The assumption of a time-independent nonradiative decay τ'' is only an approximation as the number of excited-state electrons is not constant. The solution of the rate equations results in the following expression for the PL intensity of the ground state:

$$I(t)=\bar{I}\frac{1}{\tau_1-\tau^{\rm rel}}\left[\exp\left(\frac{-t}{\tau_1}\right)-\exp\left(\frac{-t}{\tau^{\rm rel}}\right)\right], \quad (1)$$

where the time-integrated intensity $\bar{I}$ is given by

$$\bar{I}\sim N_0\frac{\tau_1}{\tau^{\rm rad}}, \quad (2)$$

and the lifetime of the holes in the ground state τ_1 is defined in the usual way as $1/\tau_1=1/\tau^{\rm rad}+1/\tau''$. N_0 is the total number of holes created per light pulse and is thus related to the absorption. We can assume that N_0 is constant or at least slowly changing with field since the laser emission is much broader than any spectral absorption bands. The ratio $\tau_1/\bar{I}$ is thus proportional to $\tau^{\rm rad}$, i.e., the optical recombination time. Due to the symmetry of Eq. (1) in the two times τ_1 and $\tau^{\rm rel}$, it is not possible to correlate the two fitted times with specific levels, but it seems to be more plausible to identify the shorter time with hole relaxation. Finally we should point out the main features of the model: (i) it incorporates the observed PL rise time by allowing for a hole relaxation and (ii) the intentity minimum at $\nu=1$ enhances the increase in radiative lifetime over that of the observed decay time τ_l.

In Fig. 2 we plot the hole lifetime τ_l and the hole relaxation time τ^{rel} obtained from fits to Eq. (1). Both times τ_l and τ^{rel} show a distinct maximum at $\nu=1$, while the intensity displays a minima identical to the cw results. In general, an increase in lifetime τ_l can be caused either by an increase in the radiative recombination time τ^{rad} or by an increase in the nonradiative time τ^{n}. However, an intensity minima accompanying an increased lifetime can only be caused by an increase in radiative decay time τ^{rad}. This is demonstrated in Fig. 3 by the large increase in $\tau_l/\bar{I} \sim \tau^{rad}$ versus filling factor ν. Figure 3 also illustrates the strong temperature dependence of the anomaly. Commensurate with the quantum Hall effect it disappears with increasing temperature and $\nu \neq 1$. In the inset of Fig. 3 we give an example of the change in τ^{rad} for the SI at $T=0.5$ K. The SI data presented here show only a factor of 3 in enhancement of τ^{rad}, however, we have data on samples with different carrier densities showing an enhancement of more than an order of magnitude. A clear dependence of the magnitude of the lifetime increase on carrier density has not been established.

Before we discuss possible mechanisms for an increased radiative recombination time, it is important to point out that this increase is likely to be the main cause for the previously reported[3] intensity maxima in the excited-state luminescence. The inset in Fig. 1 shows the measured intensity minima of the ground-state recombination (I_0) and the maxima of the excited-state recombination (I_1). It is obvious that the total PL intensity (I_0+I_1) has no significant structure around $\nu=1$. This indicates that there are no other decay channels for the hole. For the SQW the situation is similar; however, the intensity lost in the ground-state transition appears not only in the excited-state transition but also in a broadband luminescence on the low-energy side of the ground state. Thus a reduction of the ground-state matrix element leads to a relative enhancement for the competing recombination channels. It cannot be excluded here that other mechanisms, like an increased population of the excited state[10] contribute to the maxima in the excited-state PL. However, their contribution has to be small, as such absolute increases of the excited-state channel would lead to a decrease in hole lifetime instead of the observed increase.

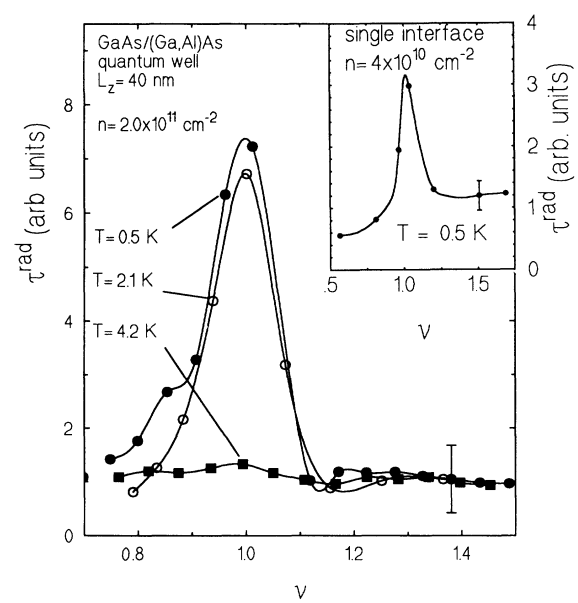

FIG. 3. Relative change of the radiative recombination time τ^{rad} for a GaAs/(Ga,Al)As single quantum well for three different temperatures. [τ^{rad} is normalized to $\tau^{rad}(\nu=1.35)=1$.] Inset: Same plot for a single interface at $T=0.5$ K. The curves are guides for the eye. Sample parameters are given in the previous figure captions.

We now consider mechanisms for the increased radiative recombination time τ^{rad} at $\nu=1$. This increase can be related directly, via Fermi's "golden rule," to a decrease in the optical transition matrix element, which is governed by the overlap integral of the electron and hole wave functions, and possible changes in the density-of-states factor. The electron-hole overlap can be separated into two spatial components involving the wave functions in (i) the z direction only and (ii) the xy plane. For the case of electron hole overlap in z direction, the average z distance of the hole from the 2D electron gas is affected by screening for the following reason. Outside of the $\nu=1$ localization regime, electrons in a partly filled Landau level form an image charge that attracts the hole towards the interface. (This mechanism is effective even though for $\nu>1$ the screening charge is composed of electrons having spins opposite to those that recombine with the hole.) On the other hand, at $\nu=1$ the spin gap prevents the formation of an image charge and the hole is repelled from the interface by the self-consistent potential. This would result in a smaller z overlap of the electron and hole wave functions at $\nu=1$, in agreement with our observation. The xy part of the overlap is also affected by screening. However, an increased overlap due to the formation of the image charge is only expected for electrons in the partially filled spin level. This leads to an asymmetry in the filling factor dependence, as the transition-matrix element would be enhanced only for $\nu<1$ where the lowest spin-split Landau level is partially empty. This may account for the slight asymmetry in the radiative recombination times seen in Fig. 3 (inset) for the SI. Another possible contribution to a change in the xy part of the overlap is due to localization of the electrons in the potential fluctuations of the remote ionized impurities. Localization is likely to reduce the overlap, as electrons and holes tend to localize in different regions of the xy plane, due to their different charges. The effect of localization is expected to be symmetric with respect to $\nu=1$, as it is caused by the lack of screening of the donor potential at $\nu=1$. A decision of whether the effect of screening on the overlap is large enough to explain the sizable changes observed in the experiment, or whether a contribution due to localization has to be taken into account, is beyond this qualitative discussion.

The increase in the hole relaxation time τ^{rel} at $\nu=1$ shows a similar temperature dependence as τ^{rad}. We note that the increase is only significant for the SQW, which could be related to the fact that the hole levels in a SI are not subject to strong confinement quantization. The mechanisms of hole relaxation in doped GaAs/$Ga_{1-x}Al_xAs$ SQW have been discussed recently in relation to a polarization anomaly of PL.[11,12] However, a theoretical analysis of a possible filling-factor dependence has not been given. A mechanism involving electron-electron interactions could explain a longer relaxation time, as the spin gap at $\nu=1$ would prohibit energy transfer from the hole to the 2D electron gas. But it has also been noted that shake-up processes are not expected to be very important for PL emission normal to the 2D layer.[12] Relaxation due to electron–acoustical-phonon interaction is expected to be enhanced by the reduced screening. A definitive explanation of the observed relaxation would have to take the complicated valence-band structure into account.

We showed that the intensity minima at $\nu=1$ in the photoluminescence of very high mobility GaAs/(Ga, Al)As is accompanied by an increase in the hole lifetime. The dramatic suppression of the radiative recombination time for the ground state is likely to be a consequence of carrier localization and lack of screening at integer Landau-level filling. The inhibited recombination of holes with electrons in the ground state also accounts for the intensity maxima in the excited-state PL. All the effects show a temperature dependence similar to the QHE. Further work on time-resolved measurements is underway in the regime of the fractional QHE and the electron solid.

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