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Photoluminescence studies of current-induced nonequilibrium states in magnetically quantized two-dimensional electron gases

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We report studies by optical techniques of current-induced nonequilibrium electron populations in magnetically quantized two-dimensional electron gases. Increasingly marked current-dependent changes with magnetic field are observed in both the energy and the intensity of the main photoluminescence features. The magnetic-field dependence of the relaxation time of nonequilibrium population following a current pulse is qualitatively in line with the severe momentum constraints on one-phonon emission. However, a theoretical treatment of this mechanism shows stronger field dependence, $\propto B^4$, than that found experimentally, $\propto B^2$, indicating the importance of parallel relaxation channels. We suggest these may involve the diffusion of excited electrons via intra-Landau-level transitions to centers in the Hall bar where relaxation can occur via inter edge-state transitions.

Photoluminescence (PL) has been widely used in the study of magnetically quantized two-dimensional electron gases (2DEG's) including the incompressible integer and fractional quantum Hall states, which produce marked signatures at low temperatures (see Refs. 1 and 2, and references cited therein). There appear, however, to have been no reports of PL studies of nonequilibrium effects such as those that arise in the presence of a transport current. In the integer quantum Hall state and below a critical current $I \leqslant I_c$, $R_{xx}=0$, so no dissipation occurs in the bulk of the 2DEG. Dissipation does occur there, however, when $I>I_c$ and at all currents for nonintegral filling factors ν. Although some of the dissipation may arise through intra-Landau-level transitions the dominant process is likely to involve the excitation of electrons to adjacent Landau levels (LL's) separated in energy by $\hbar\omega_c$, which then relax principally by acoustic-phonon emission.

In this paper we report investigations by time-resolved PL of the nonequilibrium populations of carriers produced by a current pulse at filling factors $\nu \gtrsim 1$. The current produces marked changes in the PL and the effect of increasing magnetic field in quenching the electron relaxation when the current is switched off is equally striking. The devices used are Hall bars of modulation-doped GaAs/Al$_{0.32}$Ga$_{0.68}$As heterostructures G-635 and G-644 with saturation electron densities $\simeq 1.2\times10^{15}$ m^{-2} ($\nu \sim 2.5/B$) and mobilities of a few times 10^2 m^2 V^{-1} s^{-1}.[3] They have dimensions 2×3 mm^2 with source-drain contacts and four voltage probes and their band structure is shown schematically in Fig. 1. The GaAs buffer layer is weakly doped to flatten the bands and so enhance the quality of the PL. The samples are held at $T=1.8$ K and magnetic fields B applied perpendicular to the plane of the 2DEG. The PL is excited using a low-power cw He-Ne laser beam focused in the middle of the device to an area 30μm across corresponding to a power density of $P/S \lesssim 10^{-3}$ W cm^{-2}. Time-resolved luminescence spectra are recorded with a double spectrometer and photon counting system and the resolution achieved is always better than 0.2 meV. The current I_{sd} is varied from 1 to 30 μA, corresponding to current densities from $5\times10^{-4}-1.5\times10^{-2}$ A m^{-1}, well below the value ~ 1 A m^{-1} at which quantum Hall breakdown occurs at $\nu \sim 1$ (Ref. 4, and references cited therein). The pulse length is 320 μs. Two time-resolved PL spectra are stored and averaged. A reference spectrum is

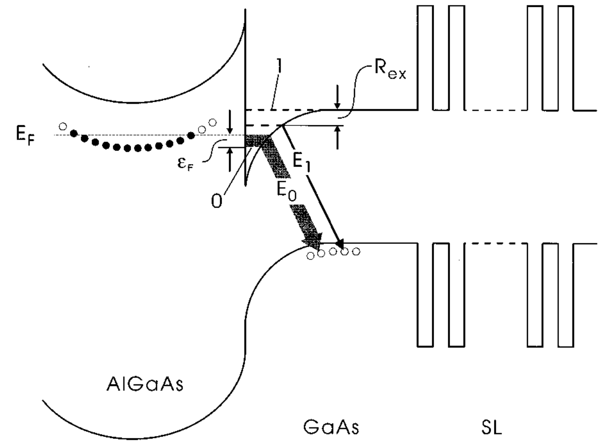

FIG. 1. Schematic diagram of the potential in and optical transitions observed from n-type modulation-doped heterostructures. 0 and 1 are the ground and the first excited 2D subbands, E_0 and E_1 are the radiative transitions between 2DEG and photoholes in the buffer layer.

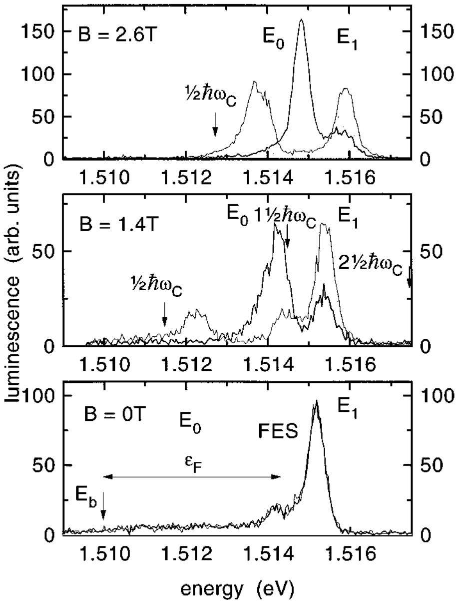

FIG. 2. PL spectra obtained at three magnetic fields. The curves shown shaded and in bold are for $I_{sd}=0$ and 30 μA, respectively.

taken using a gate interval centered 100 μs before the start of the current pulse and a second spectrum is then taken at a preset and variable time delay after the start of the pulse. The response time of the photomultiplier tube is less than 10 ns so the time resolution is determined by the width of the gate interval. The time between current pulses is increased, normally to between 6 and 10 ms, until it has no steady state effect on the data. Simultaneous measurements of the source-drain resistance are also made.

Figure 2 shows the luminescence spectra obtained for three values of magnetic field. The shaded curves are data for zero current, taken with the first gate, and the curves shown by bold lines are for current $I_{sd}=30$ μA taken with the second gate set in the middle of the current pulse. In zero magnetic field, two familiar features are observed for zero current: a broad band E_0 and a narrower (excitonic) band or line E_1. These have previously been assigned to the recombination of 2D electrons from the $n=0$ and $n=1$ subbands, respectively, of the confined potential with photocreated holes in the buffer layer[5] 10–100 nm from the plane of the 2DEG.[6] There is also a weak feature on the low-energy side of E_1 due to the Fermi-edge singularity (FES).[7] E_0 narrows as the magnetic field B is increased and its peak energy E_0^p moves by an amount proportional to $\hbar\omega_c/2$ where $\omega_c=eB/\mu$ with $\mu^{-1}=m_e{}^{*-1}+m_h{}^{*-1}$, showing that the PL arises from transitions between the lowest LL's of the 2DEG, $l_e=0$, and the photoexcited holes, $l_h=0$. The shift in E_0^p corresponds to a value of μ somewhat smaller than that calculated possibly as a result of interface strain effects.

Striking changes occur in the PL when a current flows through the 2DEG, which are qualitatively the same throughout the whole current range. No change can be detected in zero or small magnetic fields but, for fields greater than $B\sim0.5$ T, progressively larger current-dependent effects occur in both E_0 and E_1. The energy of E_0^p increases approximately linearly with current at fixed B and the increase is proportional to B. This shows that there is an increase in recombination energy in the illumination area in the middle of Hall bar that is proportional to the Hall voltage V_H and equal to CeV_H, where $C\simeq10^{-2}$.

The PL is due to the recombination of electrons in the 2DEG and photocreated holes. The holes are separated from the 2DEG but sufficiently close to it that they experience the Hall electric field F_H arising from the density gradient across the width of the 2DEG. So the electron states at the bottom of the conduction band in the 2DEG increase in energy in the direction of F_H at approximately the same rate as the electron states at the top of the valence band in the region of the holes. The Hall field-dependent blueshift in recombination energy must presumably be attributable therefore to differences in the response of the electrons and holes to the Hall field. There is no electron drift in this direction, the electric field F_H being balanced by the Lorenz force, but the holes are accelerated into excited states since in this case there is no balancing Lorenz force. (This shift would evidently be enhanced if the hole distribution increased in the direction of F_H since this would lead to a reduction in the local Hall field in the region of the holes from that in the 2DEG.) We also note that E_0^p grows in intensity with current implying an increase in the recombination rate and this may be due to the approach of E_0 to the FES.[7–9]

In contrast to E_0^p, the dominant effect of current on E_1 is a change in intensity rather than spectral position and the sign of the change can be positive or negative depending on the magnetic field. The currents would seem to be too small to produce significant changes in the exciton population and we attribute the changes in intensity to changes in the LL populations within the $n=0$ subband. These population changes would change the exciton screening and hence the recombination rate. It is well known that the intensity of exciton PL under equilibrium conditions varies strongly with filling factor being greatest when the Fermi energy lies midway between Landau levels:[5] the condition for minimum screening. As the Fermi energy rises, the increase in population of delocalized states in the upper Landau levels leads to a more compressible electron gas and so to more efficient screening and weaker intensity. The observed current-dependent changes in the E_1 peak intensity would appear to arise from similar changes in compressibility. If the Fermi energy lies within a Landau level the broadening of the Fermi distribution resulting from the rise in electron temperature when current flows leads to a reduction in screening and hence to an increase in PL intensity as seen in Fig. 3 for $\nu\sim0.75$. However, if the filling factor is close to midgap, the excitation of electrons resulting from current flow should increase the population of delocalized states and so the compressibility leading to a reduction in intensity as seen in Fig. 2 for $\nu\sim1.8$ and 1.0. The increase in excited carrier population probably occurs as a result of tunnelling between edge states followed by diffusion of the nonequilibrium carriers into the bulk of the 2DEG through the delocalized states of the upper LL.[10] We note, however, that recombination of electrons in the higher LL's is not seen in the PL spectrum in line with the orbital momentum selection rules for conduction–valence-band transitions $\Delta l=l_e-l_h=0$.

These current-dependent changes in PL have been used to study the relaxation of the nonequilibrium population of the

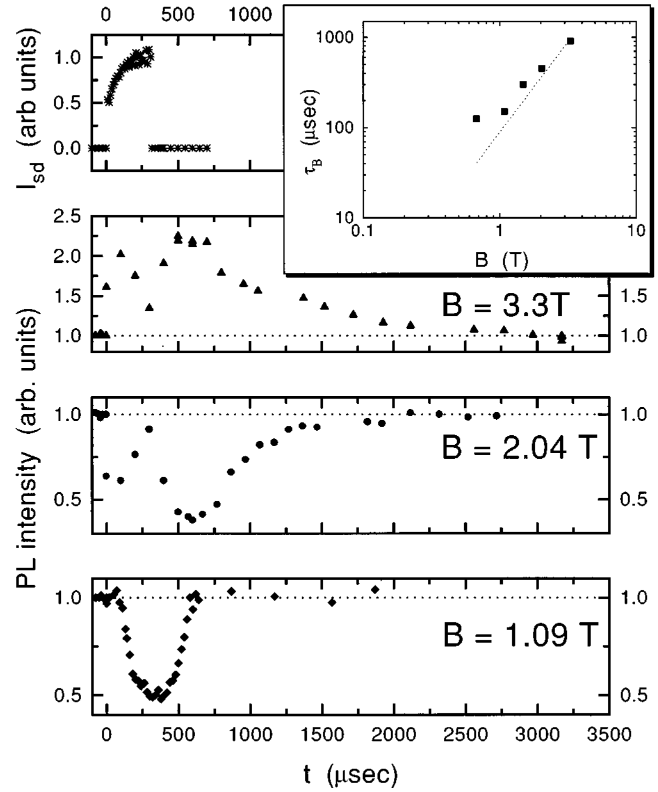

FIG. 3. The time dependence of the E_1 PL intensity for various magnetic fields: (a) $B=1.09$ T; (b) $B=2.04$ T, and (c) $B=3.3$ T. The inset shows the relaxation time determined from the approach of the PL to equilibrium as a function of B (squares); (d) the dotted line shows the fit to $\tau_B=\gamma B^2$ where $\gamma=88\pm7$ μs.

magnetically quantized 2DEG when the current is switched off. Figure 3 shows the form of the current pulse through the 2DEG and the time dependence of the PL intensity from E_1 at three different fields. At 3.3 T, as already discussed, the intensity increases during the rise time of the current and then falls back to the initial value. However, at 1.09 and 2.04 T, the intensity first falls and then rises back to the initial value. (The structure during the rise is reproducible but will not be discussed further at this stage.) This behavior is shown in more detail in Fig. 4, which shows PL spectra for $B=1.5$ T and $I_{sd}=30$ μA taken during and at four times after the end of the pulse. After 700 μs, the spectrum has essentially relaxed to that before the current pulse, which is also shown but it is evident that the relaxation of the nonequilibrium population produced by the current pulse continues for a time that is appreciably longer than the length of the pulse. The recovery time is found to increase with magnetic field B as can be seen in Fig. 3 and from the relaxation in the tail of the decay, we obtain a time $\tau(B)$, which agrees quite well with times obtained from the relaxation of the position and intensity of E_0^p and the intensity of E_1. Values of $\tau(B)$ obtained from E_1 are given in the inset to Fig. 3. At the higher fields these can be represented approximately by $\tau_B=\gamma B^n$, where n lies between 1.4 and 2 and the line shown is fitted to $\tau_B=\gamma B^2$ with $\gamma=88\pm7$ T^{-2}μs corresponding to a relaxation rate

$$\tau_B^{-1}\sim 1.1\times 10^4 B^{-2}[\mathrm{s}^{-1}]. \tag{1}$$

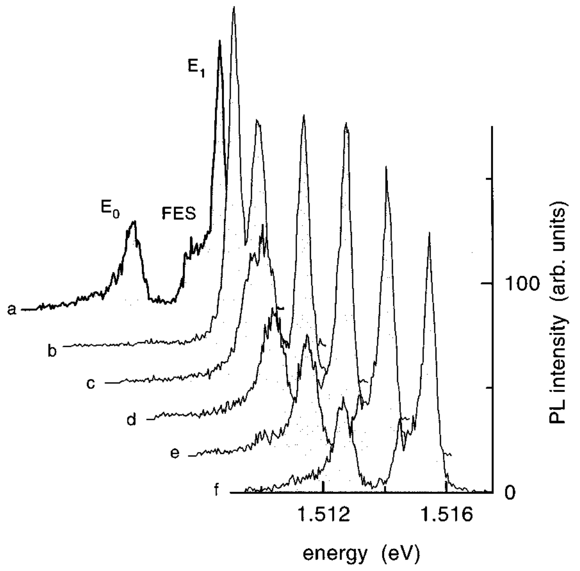

FIG. 4. PL spectra at $B=1.5$ T taken before (a) and at the following times after the end of a current pulse of $I_{sd}=30$ μA: (b) 0, (c) 140, (d) 300, (e) 500, and (f) 700 μs.

There are several processes to be considered in discussing these data. The first two, electron excitation and diffusion, have already been noted. These are followed by inter-LL relaxation and we believe that diffusion and inter-LL relaxation both play a role in the kinetics of the PL signals E_0^p and E_1. As the field is increased until the 2DEG is fully quantized ($k_BT_e \ll \hbar\omega_C$), inter-LL relaxation should initially occur predominantly through one-phonon inter-Landau-level transitions at a rate that has been shown theoretically[11] for the transition $l_e=1\rightarrow l_e=0$ to vary as

$$\tau_{1\text{-ph}}^{-1}\approx\frac{2.3\Xi^2 s^3 m^*(1-f_n^0)}{h^2\rho a^6\omega_C^4}$$
$$\sim 7\times 10^6(1-f_n^0)B^{-4}[\mathrm{s}^{-1}], \tag{2}$$

where we take $\Xi=10$ eV, $s=5.5\times10^3$ ms^{-1}, $a=6$ nm, and $\rho=5.3\times10^3$ kg^{-3} for the values of the deformation potential constant, the LA sound velocity, the width parameter of the well and the GaAs density, respectively. f_n^0 is the Fermi distribution function of the final state.

The phonon emission is constrained by in-plane momentum conservation to directions approximately normal to the 2DEG plane and the strong decrease in emission rate with field is associated with the difficulty of conserving normal momentum when the wave number of the cyclotron phonons exceeds $1/a$. The field dependence of the measured relaxation rate, B^{-n}, with n between 1 and 2, is very different from the B^{-4} for the one-phonon process suggesting that the relaxation must be taking place through a faster parallel channel. However, the one-phonon relaxation rate calculated at $B=2$ T ($1-f_n^0\sim0.25$) and using the parameters given above are $\sim$40 times faster than the measured value. We note though that the calculated rate is very sensitive to the value of a and there is some evidence that this is increased by illumination.[12] So, for example, if this were increased by $\sim$1.5 and some allowance made for the effect of screening on the electron-phonon interaction the calculated rate could be brought down to below the measured rate. The parallel channel evidently cannot be two-phonon emission even though this is calculated to become faster than the one-phonon process at fields comparable to those the highest used here[11] since its relaxation rate should vary as B. We conclude therefore that the observed relaxation process is not an intrinsic process but rather one involving fast relaxing centers to which the excited electrons diffuse. Indeed the field dependence is consistent with diffusion being the rate limiting step. We assume the time for the electrons to diffuse an average distance d before relaxing is given by the usual expression $\tau_{\text{diff}} \sim d^2/4D(B)$, where $D(B)$ is the electron diffusion coefficient in a field B.

Classically $D(B) \approx D(0)/(\mu B)^2$,[13] so that $\tau_{\text{diff}} \propto B^2$, which is approximately consistent with observation and the experimental values of τ indicate that $d \approx 30$ μm. This corresponds to a 2D density of relaxing centers $\approx 10^9$ m^{-2}. We suggest that the fast relaxing centers are edge states:[14,15] the rise in potential energy at the edges of the sample leads to the possibility of intra-Landau-level transitions of finite energy and inter-Landau-level transitions of energy less than $\hbar \omega_c$. It has been shown theoretically that, at high magnetic fields, the difficulties of conserving momentum normal to the 2DEG are appreciably less in both processes than in the one-phonon process in the bulk so that both can be appreciably faster. Since the size of d shows that most of the relaxation must be taking place in the bulk of the 2DEG rather than at the edges of the Hall bar the edge states must be located at "internal edges" associated with potential fluctuations.

We conclude that time-resolved photoluminescence provides a new and valuable method of studying nonequilibrium phenomena in magnetically quantized 2DEG's. In the present studies, in which the departure from equilibrium was produced by a transport current, the B^{-2} field dependence and the magnitude of the relaxation rate suggest that the relaxation takes place predominantly at "internal edges" around inhomogeneities (potential fluctuations) and is limited by electron diffusion to these fast relaxing centers. It seems likely that a similar process is responsible for the electron excitation. The dependence of the shift in E_0 on Hall voltage suggests the technique could be used to map the potential across the sample and measurements of this are in progress. It may also be possible to extend it to study integer quantum Hall breakdown and perhaps also to the fractional quantum Hall regime.

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