Auger Recombination within Landau Levels in a Two-Dimensional Electron Gas

M. Potemski,[(1),(2)] R. Stepniewski,[(3),(4)] J. C. Maan,[(1)] G. Martinez,[(3)] P. Wyder,[(1)] and B. Etienne[(5)]
[(1)]*Hochfeld-Magnetlabor, Max-Planck-Institut für Festkörperforshung, BP 166X, 38042 Grenoble, France*
[(2)]*Institute of Physics, Polish Academy of Sciences, 02668 Warsaw, Poland*
[(3)]*Service National des Champs Intenses, Centre National de la Recherche Scientifique, BP 166X, 38042 Grenoble, France*
[(4)]*Institute of Experimental Physics, University of Warsaw, 00681 Warsaw, Poland*
[(5)]*Laboratoire de Microstructures et de Microelectronique, Centre National de la Recherche Scientifique, 92220 Bagneux, France*
(Received 14 November 1990)

A strong emission arising from states lying higher in energy than those optically pumped is observed under interband excitation into partially filled Landau levels of a modulation-doped GaAs quantum-well structure in a magnetic field. The intensity of this emission depends quadratically on the excitation power and is strongly influenced by magnetic field through the occupancy of the Landau levels. This effect demonstrates the high efficiency of Auger processes in partially filled Landau levels of a two-dimensional electron gas.

PACS numbers: 73.20.Dx, 78.20.Ls, 78.65.−s

A direct experimental proof of Auger recombination would consist of an observation of the related up-energy conversion. Such a process in which the energy released by one electron, when relaxing to a lower-lying state, is transferred to another electron, excited into a higher-lying state, has been evidenced for discrete atomic orbitals[1] and also for band states of semiconductors[2,3] but usually in an indirect way. We have investigated an atomiclike system which consists of the discrete equidistant Landau levels of a quasi-two-dimensional electron gas, as can be found in modulation-doped semiconductor heterostructures with a magnetic field applied perpendicular to the two-dimensional layers. In this case, particular states can be selectively optically excited and discrete lines are observed in emission. Furthermore, the number of electrons at each level can be tuned by the magnetic-field strength. We show in this Letter that, with interband optical excitation, an emission arising from states lying higher than those pumped by the laser can be detected. This emission is observed at low temperatures ($kT \simeq 0.15$ meV) and for low excitation powers ($P_{\mathrm{exc}} \lesssim 10\ \mathrm{W\,cm^{-2}}$) and can be as high as 9 meV above the excitation energy. Strikingly enough, its intensity may be comparable to that of the luminescence arising below the excitation. This is in contrast with what has been reported for bulk semiconductors[4] where the related intensity has been found to be several orders of magnitude lower than the intensity of the conventional luminescence. The up-conversion of energy is attributed to electron-electron scattering processes (shakeup of the Fermi sea[5]) occurring within the quantized Landau levels of the two-dimensional electron gas.

The results have been obtained on a one-side modulation-doped *n*-type GaAs/GaAlAs single quantum well with a well thickness of 250 Å and an electron sheet concentration of $n_s = 7.6 \times 10^{11}\ \mathrm{cm^{-2}}$. In this sample the zero-electric subband is occupied and the Fermi level is located very close to the bottom of the first subband.[6] Representative magnetoluminescence and magnetoluminescence-excitation spectra, for σ^+ polarized light, are shown in Fig. 1(a).[7] It is clear that one can easily assign the peaks related to the two-dimensional structure and separate them from the bulk luminescence. The Landau-level fan chart of the optically allowed transitions observed in luminescence and luminescence-excitation spectra is shown in Fig. 1(b). The Fermi-level position as determined from the onset of the excitation spectra [visualized with the dashed line in Fig. 1(b)] is in perfect agreement with transport data. The jumps of the Fermi level occurring at $B = 5.3$, 7.95, and 15.9 T correspond to full occupation of three, two, and one Landau levels, respectively (filling factor including spin degeneracy $\nu = 6$, 4, and 2, respectively). Since the cyclotron energy for the valence band is relatively small, a single valence-band level is assumed in this paper.

At fields of around 9.5 T the lowest Landau level L_0 is fully occupied, whereas the first Landau level L_1 is partially empty. When we excite electrons into this L_1 level, a strong emission at energies higher than the laser energy is observed together with the normal luminescence coming from L_0 [Fig. 2(a)]. This higher-energy emission originates from the zero Landau level of the first electric subband, L_0', which is the nearest empty electronic state of higher energy than L_1. The excitation spectrum of the luminescence related to L_0' [Fig. 2(a)] shows not only the usual pseudoabsorption transitions above the emission energy, but also a clear maximum below the detected energy, when the excitation energy coincides with L_1.

A schematic model explaining our experimental results is shown in Fig. 2(b). Electrons from valence-band states are excited into the L_1 Landau level and thereby empty states can be created in L_0 when the L_0 electrons recombine with photoinduced holes. Two electrons on L_1 may interact, deexciting one to the lower L_0 level, losing $\hbar\omega_c$, and exciting the second to the higher empty level

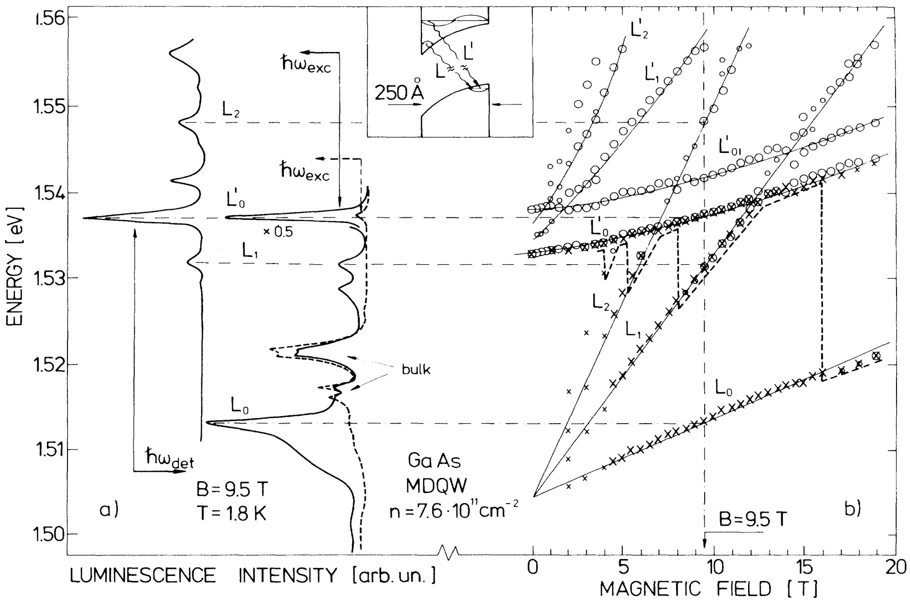

FIG. 1. (a) Intensity of the luminescence detected at $\hbar\omega_{\rm det}$, as a function of the exciting energy (left) and luminescence spectra at different excitation energies $\hbar\omega_{\rm exc}$ (right). Two-dimensional and bulk structures are observed when the excitation energy corresponds to the peak of the two-dimensional density of states (solid line), and mainly bulk-related luminescence is visible when exciting in the gap between the two-dimensional levels (dashed line). (b) The Landau-level fan chart of the optically active transitions observed in luminescence (crosses) and luminescence-excitation (open circles) spectra. The size of the symbol reflects the transition intensity. The L_{01}' absorption line involves the light-hole level. The Fermi-level position is shown with the dashed line.

L_2, gaining $\hbar\omega_c$, conserving energy in the process. Such mechanisms are always possible but are usually not experimentally observable because the carriers excited to L_2 by the Auger process will relax rapidly to the L_1 state before recombining optically. However, in this particular system, the carriers excited to L_2 can be observed since they can relax first to L_0' and then recombine, giving rise to a luminescence at energies above the laser excitation.

Recent experimental results[6,8-10] show that L_0', which is associated with the first empty electric subband, has an excitonic character even in doped samples. Therefore electrons on the L_0' level are strongly correlated with individual holes, leading to a remarkably efficient radiative electron-hole recombination compared to the thermalization of electrons towards states of lower energy. The emission peak related to the L_0' level is then always visible in "normal" (exciting at higher energies) luminescence spectra, even if empty states exist at lower energies [see Fig. 1(a)]. This allows us to use this excitonic recombination as a "trap detector" of Auger electrons.

To study more in detail the above-laser emission we have measured its intensity in the range of magnetic fields between 7.95 and about 12 T (when the Fermi level is pinned to the L_1 Landau level) and also in the range between 5.3 and about 6.4 T (in this case the L_2 Landau level is partially empty and lies below L_0' and similar processes like those described in Fig. 2 may occur involv-

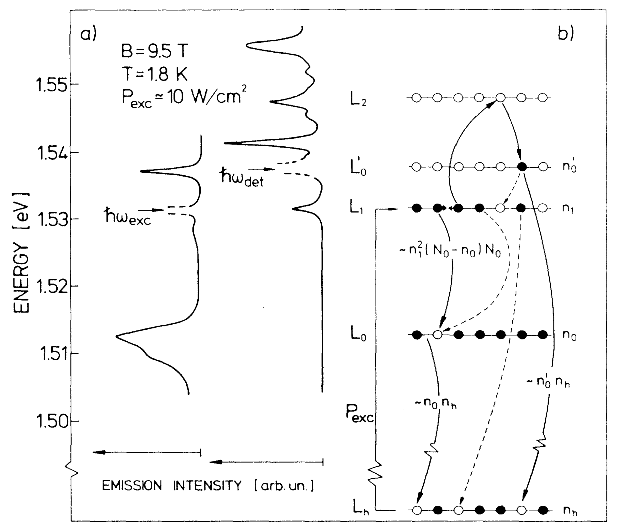

FIG. 2. (a) Luminescence spectra observed under excitation into the partially occupied Landau level L_1 ($\hbar\omega_{\rm exc}$) below and above the laser energy (left) and intensity of the above-laser emission ($\hbar\omega_{\rm det}$) as a function of the exciting energy (right). (b) Schematic picture of the recombination processes explaining the above-laser emission. The relevant processes are shown with solid lines, other relaxation-recombination channels with dashed lines. n_i, n_i' (n_h) denote the electron (hole) concentrations on Landau levels L_i, L_i' (L_h). $N_0 = 2eB/h$ is the degeneracy of the Landau level.

ing now L_2, L_0', and the next empty Landau level L_3). The changes of I_0', the peak intensity of the above-laser emission, with magnetic field are shown in Fig. 3(a) (solid circles). In both cases ($\nu \lesssim 4$ and $\nu \lesssim 6$) a sharp onset is observed at lower magnetic fields followed by a saturation of the intensity at higher fields. The dependence of I_0' with excitation power P_{exc} is quadratic on P_{exc} in the range of low excitation powers [Fig. 3(b)] and linear on P_{exc} at high excitation powers. The dependence of the intensity I_0 of the luminescence associated with L_0 is also shown in Fig. 3. In both cases (magnetic-field and power dependences) the variations of I_0' and I_0 are clearly different showing their different origin. Quantitatively, it is easy to reproduce the dependence of I_0' on P_{exc} by solving the rate equations at a fixed magnetic field. This analysis gives the quadratic dependence of I_0' as long as the radiative recombination rate from the L_0' level is small compared to the thermalization rate down to the partially empty L_1 state, i.e., when the L_0'-related emission is not a dominant recombination channel. This is no longer true for the highest excitation power when I_0' shows a linear dependence. As a matter of fact, the quadratic power dependence must saturate because otherwise the energy-conservation law would be violated.

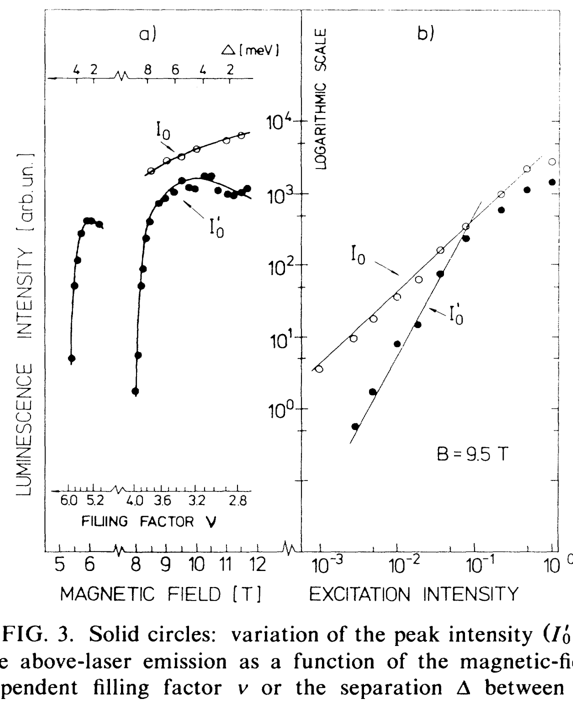

FIG. 3. Solid circles: variation of the peak intensity (I_0') of the above-laser emission as a function of the magnetic-field-dependent filling factor ν or the separation Δ between the excitation- and the emission-peak energies. The peak intensity of the L_0-related luminescence (I_0) is shown with open circles. Solid lines are guides for the eye. (b) Power dependence (in relative units) of the I_0' and I_0 when exciting into the L_1 level. Solid lines represent quadratic (for I_0') and linear (for I_0) variations.

To reproduce the magnetic-field dependence with the same quantitative analysis is more difficult because one should take into account the effects of nonparabolicity, broadening of Landau levels, filling-factor-dependent screening, etc., which is beyond the scope of this paper. However, the onset is clearly related to the field where empty states appear in the L_1 level at $\nu = 4$ (L_2 at $\nu = 6$). The saturation is explained by the magnetic-field-induced decrease of the electron concentration n_1 on L_1 (n_2 on L_2, respectively) which leads to a decrease of the Auger process efficiency.

Processes similar to those shown in Fig. 2(b) may occur for all Landau levels with indexes $n \gtrsim 1$ but not for $n=0$. However, we have also observed a recombination from L_0' when exciting into L_0 for $B \gtrsim 15.9$ T field beyond which the L_0 level becomes partially empty [see Fig. 1(b)]. Since, in this case, the emission intensity is at least 2 orders of magnitude lower than when Landau levels with higher indices are excited, this effect must be of a different origin. Indeed, under excitation of electrons into the L_0 level, a new emission appears in the gap, below the laser energy, at a distance approximately equal to the separation between L_0 and L_0' levels. This would indicate an impurity-assisted process, a virtual Auger process,[11] or resonant Raman scattering.

Using cyclotron absorption saturation and cyclotron emission experiments in different bulk semiconductors,[3,12] it has been established that the Auger process becomes an important mechanism in the recombination between Landau levels. Although we deal here with a very different situation, namely, having discrete Landau levels which are already populated even at thermal equilibrium and this population is only slightly changed under optical excitation, we can also directly see from our data the efficiency of the Auger recombination. In fact, at high excitation power (in the linear regime of the I_0' power dependence) the intensity I_0' of the above-laser emission is given directly by the flux of promoted carriers through Auger processes: $I_0' = n_p/\tau_{Auger}$, where n_p is the quasistationary concentration of empty places on the L_0 level. The intensity I_0' of luminescence below the laser energy is equal to the sum of the flux of electrons deexciting by Auger processes and the flux of electrons relaxing with emission of photons or phonons,[13] i.e., $I_0 = n_p/(1/\tau_{Auger} + 1/\tau_{ph})$. At $B=9.5$ T and at high excitation power [see Fig. 2(a)] the ratio of integrated intensities $I_0/I_0' \simeq 3$, and therefore at this field $\tau_{Auger}/\tau_{ph} \simeq 2$. In general, the Auger flux is a complicated function of magnetic field and excitation power and therefore it is impossible to give a single quantity for the Auger rate; instead, a full analysis of the field and power dependences can be given. Such an analysis is in progress but falls beyond the scope of this Letter. Under some simplifying assumption we have estimated that $\tau_{Auger} \sim 5 \times 10^{-11}$ s at $P_{exc} \simeq 10$ W/cm^2 and $B=9.5$ T i.e., when the electron concentration on the partially filled L_1 level is $n_1 = 3\times10^{11}$ cm^{-2} and photocreated hole concentration is $\sim 10^{11}$ cm^{-2}. This time value would correspond to the electronic Auger lifetime obtained from cyclotron resonance experiments[12] for bulk GaAs at $n_1 \simeq 5\times10^{14}$ cm^{-3}.

An enhancement of the Auger recombination rate in two-dimensional systems may be expected due to the effect of reduced screening-enhanced correlation effects.[5,14] Our observations are in agreement with recent experimental studies[15] which show that electron-electron interactions yield the relevant contribution to carrier thermalization in GaAs modulation-doped quantum wells.

In summary, it has been shown that the observation of an emission arising from states lying higher than those optically excited can be understood in terms of Auger-type processes occurring within the electronic Landau levels of two-dimensional semiconductor structures. We believe that our observation, together with proper theoretical calculations, could lead to a deeper understanding of electron-electron interaction in two-dimensional semiconductor systems.

We thank H. Krath for his professional technical assistance and W. Knap and A. Raymond for their cooperation at an earlier stage of this work. H. Przybylinska and A. Witowski are acknowledged for helpful discussion. V. Thierry-Mieg is acknowledged for her assistance in the growth of the samples. The Service National des Champs Intenses is "Laboratoire associé à l'Université Joseph Fourier de Grenoble."

[1]For a review, see W. Bambynek, B. Craseman, R. W. Fink, H. U. Fink, H. Mark, C. D. Swift, R. E. Price, and P. Venugopala Rao, Rev. Mod. Phys. **44**, 716 (1972).

[2]P. T. Landsberg, C. Rhys-Roberts, and P. Lal, Proc. Phys. Soc. **84**, 915 (1964); see also A. Hangleiter and R. Häcker, Phys. Rev. Lett. **65**, 215 (1990), and references therein.

[3]E. Gornik, T. Y. Chang, T. J. Bridges, V. T. Nguyen, J. D. McGee, and W. Müller, Phys. Rev. Lett. **40**, 1151 (1978).

[4]G. Benz and R. Conradt, Phys. Rev. B **16**, 843 (1977).

[5]L. J. Sham, J. Phys. (Paris), Colloq. **48**, C5-381 (1987).

[6]R. Stepniewski, M. Potemski, H. Buhmann, D. Toet, W. Knap, A. Raymond, G. Martinez, J. C. Maan, and B. Etienne, in *Proceedings of the Twentieth International Conference on Physics of Semiconductors, Thessaloniki, 1990,* edited by E. M. Anastassakis and J. D. Joannopoulos (World Scientific, Singapore, 1990), p. 1282.

[7]We neglect in this paper the forbidden transitions discussed in Ref. 6 observed in luminescence (e.g., the lower component of the L_1-related doublet which is observed in luminescence but not in excitation spectra).

[8]W. Chen, M. Fritze, A. V. Nurmikko, D. Ackley, C. Colvard, and H. Lee, Phys. Rev. Lett. **64**, 2434 (1990).

[9]R. Stepniewski, W. Knap, A. Raymond, G. Martinez, J. C. Maan, and B. Etienne, Surf. Sci. **229**, 529 (1990).

[10]A. J. Turberfield, S. R. Hayens, P. A. Wright, R. A. Ford, R. G. Clark, J. F. Rayan, J. J. Harris, and C. T. Foxon, Phys. Rev. Lett. **65**, 637 (1990).

[11]P. T. Landsberg, Phys. Status Solidi **15**, 623 (1966).

[12]G. R. Allan, A. Black, C. R. Pidgeon, E. Gornik, W. Seidenbusch, and P. Colter, Phys. Rev. B **31**, 3560 (1985); see also E. Gornik, Physica (Amsterdam) **127B**, 95 (1984).

[13]J. F. Rayan, R. A. Taylor, A. J. Turberfield, A. Maciel, J. M. Worlock, A. C. Gossard, and W. Wiegmann, Phys. Rev. Lett. **53**, 1841 (1984).

[14]A. E. Ruckenstein and S. Schmitt-Rink, Phys. Rev. B **35**, 7551 (1987).

[15]W. H. Knox, D. S. Chemla, G. Livesen, J. E. Cunningham, and T. E. Henry, Phys. Rev. Lett. **61**, 1290 (1988).