Optically detected cyclotron-resonance studies of radiative processes in $Al_xGa_{1-x}As/GaAs$ high-electron-mobility structures

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The nature of radiative recombination processes in high-electron-mobility $Al_xGa_{1-x}As/GaAs$ heterostructures is revealed from optically detected cyclotron resonance (ODCR) experiments. A mechanism of ODCR detection is observed and is related to the band bending across the GaAs active layer caused by impact ionization of shallow donors and acceptors by carriers heated at CR conditions. The results of the ODCR experiments are compared with those obtained from photoluminescence measurements under an applied gate voltage.

I. INTRODUCTION

Modulation-doped high-electron-mobility (HEM) structures were introduced in order to spatially separate charge carriers from their mobility limiting parent impurities.[1,2] In the n-type modulation-doped $Al_xGa_{1-x}As/GaAs$ heterostructures electrons from donors in the $Al_xGa_{1-x}As$ barrier are transferred to the GaAs layer, which results in their accumulation in a quasitriangular potential on the GaAs side of the interface. The mobility of the so-obtained two-dimensional (2D) electron gas is further increased by introducing an undoped $Al_xGa_{1-x}As$ spacer separating the doped $Al_xGa_{1-x}As$ from the GaAs layer.

Optical properties of such structures were first reported by Yuan *et al.*[3,4] The so-called H-band photoluminescence (PL) emission was observed and attributed to the radiative recombination of the 2D electron gas accumulated at the $Al_xGa_{1-x}As/GaAs$ heterointerface with quasi-2D holes (HB1).[5] This interpretation of the H-band PL emission was recently confirmed by the optically detected cyclotron resonance (ODCR) experiments of Chen *et al.*[6,7]

The electron-hole (e-h) interaction leading to exciton binding varies with the concentration of the 2D electron gas. It can be reduced due to the weak screening of the Coulomb interaction and phase-space filling effects and also the electron-hole spatial separation. Excitons are usually not observed for concentration of the 2D electron gas exceeding $\sim 3\times 10^{11}$ cm^{-2}.[8] Electronic states due to e-h correlation can, however, still exist for carriers at the Fermi level. The 8181-Å emission of the $Al_xGa_{1-x}As/GaAs$ HEM structure is interpreted as such Fermi-level singularity (FES).[8] The 2D character of the FES PL was clearly demonstrated in the recent ODCR investigations.[6,7]

Another H-band PL emission (HB2) at lower photon energy was reported by Kukushkin, von Klitzing, and Ploog[5] and Zhao *et al.*[10] This band, attributed to the radiative recombination of the 2D electrons with holes localized at acceptors in the GaAs layer, can be observed for the structures with an increased residual dopant concentration in the GaAs layer and is separated from the HB1 band by a constant energy. The HB2 band dominates the PL spectrum until all available acceptors are photoneutralized and free holes are available for recombination with the 2D electrons, then the HB1 band rapidly increases and becomes dominant.

The properties (e.g., intensity, spectral position and shape, decay time) of the two H bands strongly depend on the sample design and experimental conditions. This is due to the fact that the potential across the GaAs active layer depends on the excitation conditions.[9] The band bending is reduced when photoexcited electrons and holes neutralize ionized donors in the barrier and acceptors in the active layer and accumulate near the $GaAs/Al_xGa_{1-x}As$ interfaces.[11] The reduction of the band bending results in a spectral blueshift of the two HB PL emissions (towards a shorter wavelength). Also the relative intensity of the HB1 and HB2 PL emissions rapidly changes with the excitation intensity.[9] Both HB bands increase in intensity with increasing excitation intensity.

The above properties of the 2D PL emissions are demonstrated in the present study based on the results of ODCR experiments. These ODCR investigations were performed under excitation with photon energies above the $Al_xGa_{1-x}As$ band gap, i.e., under different conditions than in the previous ODCR studies in which a direct excitation of the GaAs active layer was used.[6,7] The results of the ODCR experiments are compared with those obtained from PL studies performed under an applied gate voltage.

II. EXPERIMENT

ODCR experiments were performed on a converted X-band electron spin resonance spectrometer Bruker 200 equipped with an Oxford Instruments helium gas flow cryostat, working in the temperature range of 2–300 K. A p-i-n diode was used for on-off modulation of microwaves, which was driven at 970 Hz by an external generator from a lock-in amplifier. The 514.5-nm line of the Coherent Innova Ar^+ laser was used as the PL excitation source. Low-resolution PL spectra and the spectral dependence of the ODCR signal (denoted as ODCR-PL) were obtained with a 0.25-m single grating Jobin-Yvon monochromator and detected with a North Coast Ge detector.

The high-resolution PL investigations were performed on gated samples mounted in a Thor Cryogenics bath cryostat at a temperature of 2 K. A tunable Ti:sapphire laser set at 7900 Å was used as the excitation source. The PL signal was collected with lenses, dispersed in a 1-m Spex monochromator and detected by a GaAs photomultiplier tube using lock-in technique.

A semitransparent metal gate consisting of approximately 10-Å Cr and 50-Å Au was evaporated on top of the GaAs cap layer and thin electrical wires were contacted on the metal gate and the GaAs substrate. The applied electric field was thus perpendicular to the layers in the sample.

The energy band diagram of the HEM structure studied is shown in the inset of Fig. 1. The n-type modulation-doped $Al_xGa_{1-x}As$/GaAs ($x=0.35$) heterostructure consists of a 2000-Å GaAs buffer, a 24-period GaAs/AlAs short period (20 Å) superlattice (SL), followed by a 500-Å undoped GaAs active layer, a 200-Å undoped $Al_xGa_{1-x}As$ spacer, an 800-Å Si-doped (10^{18} cm^{-3}) n-type $Al_xGa_{1-x}As$ layer, and finally a 50-Å undoped GaAs cap layer. The heterostructure was grown by the molecular beam epitaxy method at 680 °C. In such a structure the 2D electron gas accumulates at the upper $Al_xGa_{1-x}As$/GaAs heterointerface. The hole states are also 2D confined. The latter is a consequence of the band bending in the active GaAs layer.

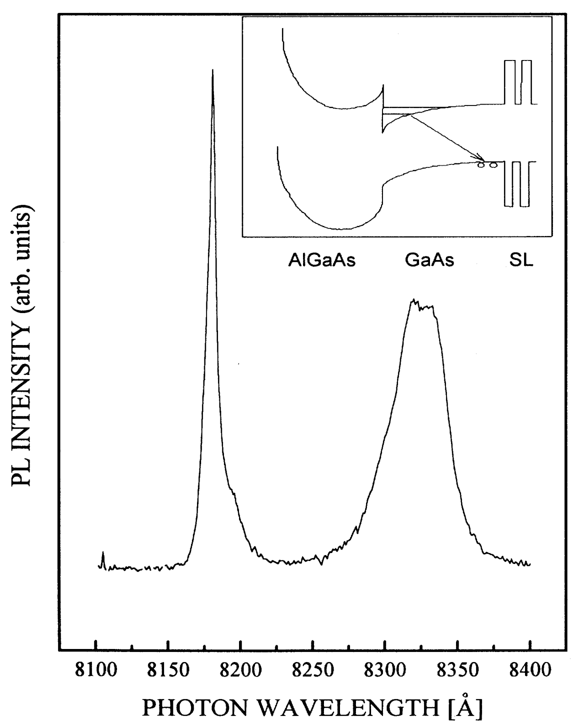

FIG. 1. High-resolution photoluminescence spectrum of the n-type modulation-doped HEM structure measured at 2 K under 7900-Å excitation. In the inset the energy band diagram of the n-type modulation-doped $Al_xGa_{1-x}As$/GaAs heterostructure is shown. The 2D electrons accumulate at the heterointerface. Also holes are confined due to the band bending in the GaAs active layer. The 2D electrons recombine with either free holes (HB1) or with holes bound at acceptors (HB2).

III. RESULTS

In Fig. 1 we show a high-resolution PL spectrum measured at 2 K under 7900-Å excitation. The PL spectrum consists of a strong FES emission at 8181 Å superimposed on a weaker HB1 band at lower energy. The PL band at 8325 Å is dominated by donor-acceptor-pair (DAP) transitions from bulk GaAs (the buffer layer). Some contribution from the HB2 PL will be suggested later on based on the ODCR results.

In Fig. 2 we show electron-cyclotron-resonance spectra of the HEM structure detected via a change in the inten-

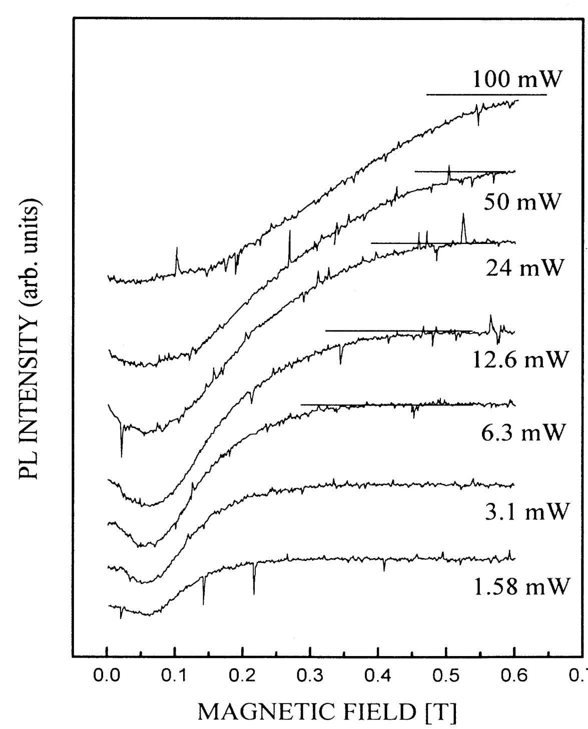

FIG. 2. The microwave power dependence of the 2D electron cyclotron resonance measured with the detection set at the 8181-Å photoluminescence emission and magnetic field normal to the heterointerface.

sity (decrease) of the 8181-Å PL band with the magnetic field set normal to the interface plane. The 8181-Å PL band is reduced by the applied microwave power by about 27% and shifts towards lower energy. A strong anisotropy of the cyclotron resonance (CR) was observed. Such an anisotropy results from the carrier confinement at the heterointerface or in the quantum well[6,7,12,13] and the angular variation of the CR signal with respect to the external magnetic field provides the evidence of the 2D character of the PL emission. CR's of 3D electrons (holes) of the GaAs substrate and the $Al_xGa_{1-x}As$ barrier should contribute to the ODCR signal since carriers were photoexcited in the $Al_xGa_{1-x}As$ barrier and also in the substrate. These CR's should, however, be heavily damped due to lower mobilities of 3D carriers. The microwave power dependence of the CR signal was measured. The CR signal broadens with the increase of the microwave power, and its intensity and width saturate for a power higher than 24 mW. We have also observed that for an increasing microwave power the CR signal could be detected via a decrease in the intensity of the 8325-Å PL band. The CR signal detected via this band was also anisotropic, indicating some contribution of the 2D electron gas to the 8325-Å PL. This we relate to the underlying HB2 PL emission.

The 8181-Å and the 8325-Å PL bands show a threshold dependence on the microwave power applied. The threshold dependence shown in Fig. 3 is a fingerprint of the impact ionization mechanism of the ODCR detection, since hot carriers must accumulate the energy equal or larger than the binding energy before the impact ionization processes can take place.[13] The decrease in the intensity of the 8181-Å PL band is accompanied by its redshift (see Fig. 4) from 8181 Å (at 0.79 mW) to about 8236 Å at 200-mW microwave power.

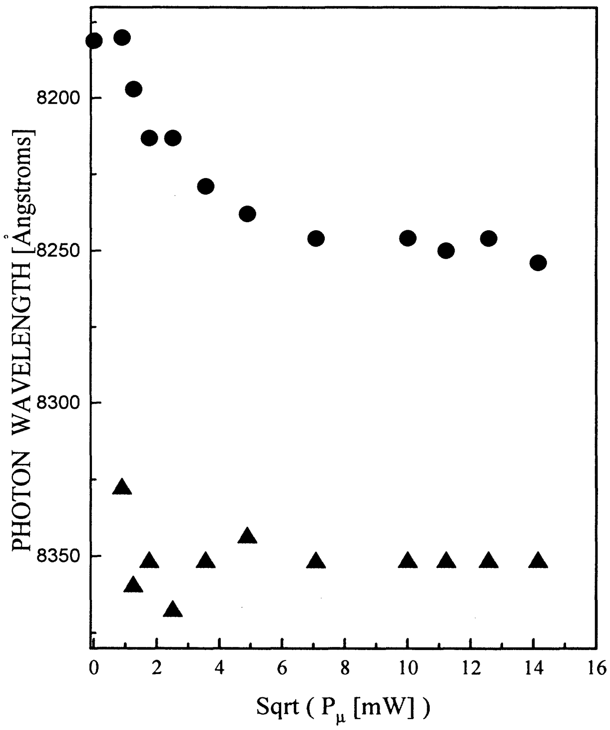

FIG. 4. The microwave power dependence of the spectral position of the two photoluminescence emissions measured in phase with on-off modulated microwave power at 970 Hz.

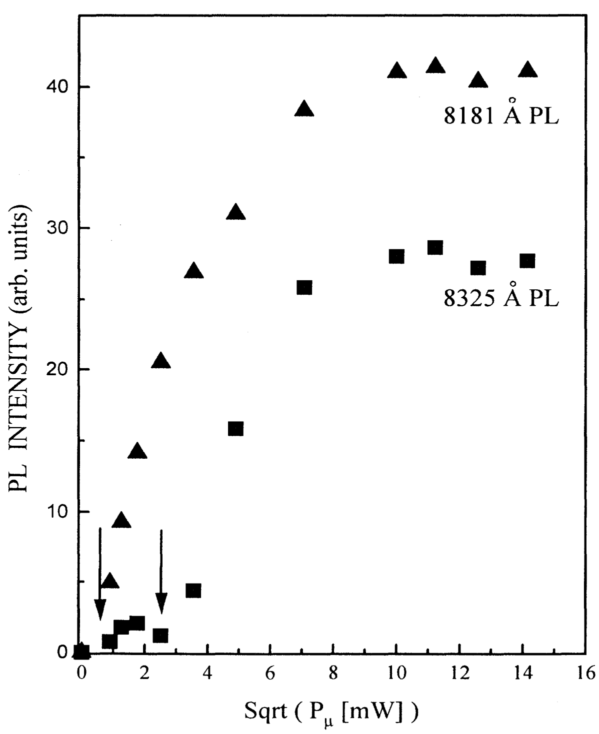

FIG. 3. The microwave power dependence of the two photoluminescence bands. The 8181-Å and the 8325-Å bands show a threshold dependence on the microwave power applied indicating an impact ionization mechanism of the ODCR detection.

IV. DISCUSSION

The PL and its response to carrier heating under CR conditions described above is different from the data observed previously on a different HEM structure under direct band-band excitation of the GaAs.[6,7] The PL spectrum, under the condition of direct band-band excitation of the GaAs, was dominated by three emissions denoted as the X,[14] the H band (HB1), and the DAP emission.[6,7] The application of a microwave field affected all these emissions. The H band was enhanced with the microwave radiation, while the X band was decreased. The X band was interpreted as the FES emission. Following this interpretation a decrease of the X band was related to a breakdown of the carrier correlation effects due to a heating microwave field. This reduces carrier recombination via the X band (FES) channel and enhances the H band (HB1) emission intensity. No "drastic" spectral shift of the PL bands was resolved in the previous ODCR experiment. This is in contrast with a redshift of the 8181-Å FES PL observed in our study. Only a small redshift, if any, is observed for the second PL band, which was expected since this PL spectrum was dominated by the bulk 3D DAP transitions. This redshift of the PL position, as explained below, and the threshold dependence of the effect on the microwave power indicate that the ODCR detection can be related to the band bending across the GaAs active layer caused by the impact ionization processes. This interpretation is based on the results of the PL experiments performed under an applied gate voltage. By applying a positive gate voltage to the HEM structure one increases the band bending in the GaAs active layer. This, as shown in Fig. 5, results in a small redshift of the FES PL, which disappears at higher positive gate voltage, and a larger shift of the HB1 PL. The shift of the spectral position of the HB1 emission is also accompanied by a strong decrease of its intensity. The latter is due to the reduced overlap between the wave functions of the 2D electrons and holes, which are spatially separated in the GaAs active layer.

For the above-band-gap excitation of $Al_xGa_{1-x}As$ free carriers photogenerated in the barrier neutralize ionized donors. This reduces band bending across the heterointerface (shown in Fig. 1). By applying a positive gate voltage one can increase the localization of the 2D electrons at the $Al_xGa_{1-x}As/GaAs$ heterointerfaces and holes at the SL interface. In agreement with the recent calculations of Weegels *et al.*,[11] the band bending across the GaAs active layer is then increased and the PL intensity should be reduced.

Weegels *et al.*[11] claimed that carrier localization is the main contribution to the band bending across the GaAs active layer. The present ODCR results indicate that the impurity ionization in the AlGaAs barrier is also important in our case. The threshold dependence of the PL intensity on the microwave power is the indication of the impact ionization processes of, first, shallow donors and then (for higher microwave powers) of shallow acceptors in the AlGaAs barrier and, if present, in the GaAs active layer by carriers heated under the CR conditions. The observed small reduction of the 3D bulk DAP emission indicates that impact ionization processes can also take part in the GaAs substrate. It should also be pointed out that the spectral shift of the 8181-Å ODCR PL is similar to that observed in the PL study under the positive gate voltage. This shows an important role of neutralization and ionization processes on the resulting band bending in the GaAs active layer.

One of the important advantages of the ODCR method over the conventional CR study is the possibility of partial photoneutralization of ionized impurities by the photoexcitation.[13,15,16] This property of the ODCR method is confirmed by the present ODCR investigations. The microwave power dependence of the mobility of 2D electron gas, as derived from the present ODCR study, varies from about 1.1×10^6 cm^2/V s at low microwave power to 2×10^5 cm^2/V s for 200 mW microwave power. It is larger than the dark Hall mobility of our structure (5×10^4 cm^2/V s) and slightly larger than the Hall mobility measured after illumination of the sample (4×10^5 cm^2/V s).

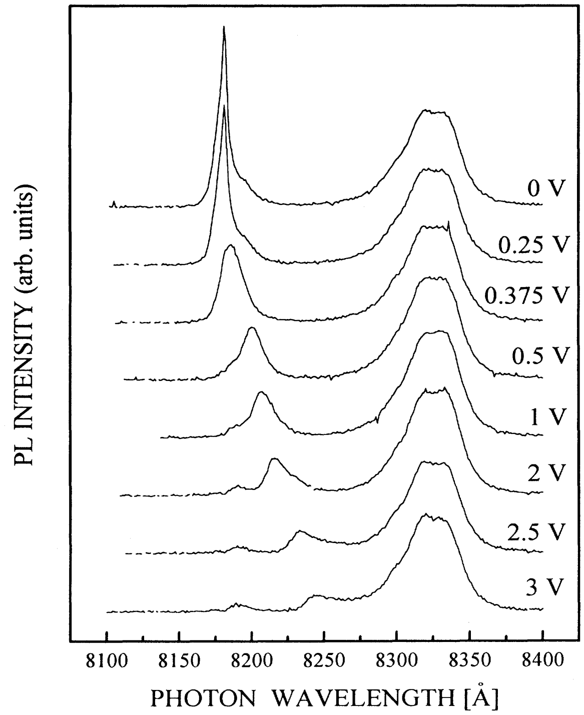

FIG. 5. The high-resolution photoluminescence spectrum of the *n*-type modulation doped HEM structure measured under positive gate voltages, which increases the band bending in the GaAs active layer.

The effective mass of the 2D electron gas in the GaAs active layer should depend on the electron concentration.[17] The resolution of the present ODCR experiment was, however, too low to resolve such a concentration dependence.

V. CONCLUSIONS

The ODCR experiments performed confirm the attribution of the 8181-Å PL band to a radiative recombination of the 2D electrons. This band is attributed to the Fermi-level singularity emission. A mechanism of the ODCR detection is observed. The impact ionization of shallow donors in the $Al_xGa_{1-x}As$ barrier and in the active region of the HEM structure, respectively, modifies the band bending across the heterostructure and thus the concentration of free carriers and their recombination rates. This results in a modulation of the PL intensity under microwave pulses in the ODCR experiment. These results are shown to be consistent with the PL results under an applied gate voltage, where the band bending is modified by the external electric field.

[1]R. Dingle, H. L. Störmer, A. C. Gossard, and W. Wiegmann, Appl. Phys. Lett. **33**, 665 (1978).

[2]H. L. Störmer, R. Dingle, A. C. Gossard, W. Wiegmann, and R. A. Logan, Solid State Commun. **29**, 705 (1979).

[3]Y. R. Yuan, K. Mohammed, M. A. A. Pudensi, and J. L. Merz, Appl. Phys. Lett. **45**, 739 (1984).

[4]Y. R. Yuan, M. A. A. Pudensi, G. A. Vawter, and J. L. Merz, J. Appl. Phys. **58**, 397 (1985).

[5]I. V. Kukushkin, K. von Klitzing, and K. Ploog, Phys. Rev. B **37**, 8509 (1988).

[6]W. M. Chen, B. Monemar, Q. X. Zhao, P. O. Holtz, M. Sundaram, J. L. Merz, and A. C. Gossard, Surf. Sci. **229**, 484 (1990).

[7]W. M. Chen, B. Monemar, E. Sörman, P. O. Holtz, M. Sundaram, J. L. Merz, and A. C. Gossard, Semicond. Sci. Technol. **7**, B253 (1992).

[8]D. Huang, H. Y. Chu, Y. C. Chang, R. Houdre, and H. Morkoc, Phys. Rev. B **38**, 1246 (1988).

[9]P. O. Holtz, B. Monemar, and J. L. Merz, in *Semiconductor Interfaces and Microstructures,* edited by Zhe Chuan Feng (World Scientific, Singapore, 1992), p. 93.

[10]Q. X. Zhao, J. P. Bergman, P. O. Holtz, B. Monemar, C. Hallin, M. Sundaram, J. L. Merz, and A. C. Gossard, Semicond. Sci. Technol. **5**, 884 (1990).

[11]L. M. Weegels, J. E. M. Haverkort, M. R. Leys, and J. H. Wolter, Phys. Rev. B **46**, 3886 (1992).

[12]B. C. Cavenett and E. J. Pakulis, Phys. Rev. B **32**, 8449 (1985).

[13]M. Godlewski, W. M. Chen, and B. Monemar, CRC Crit. Rev. Solid State Mater. Sci. **19**, 241 (1994).

[14]R. M. Kusters, J. Singleton, G. Gobsch, G. Paasch, D. Schulze, F. A. Wittekamp, G. A. C. Jones, J. E. F. Frost, D. C. Peacock, and D. A. Ritchie, Superlatt. Microstruct. **9**, 55 (1991).

[15]R. Romestain and C. Weisbuch, Phys. Rev. Lett. **45**, 2067 (1980).

[16]G. R. Johnson, B. C. Cavenett, T. M. Kerr, P. B. Kirby, and C. E. C. Wood, Semicond. Sci. Technol. **3**, 1157 (1988).

[17]A. S. Plaut, I. V. Kukushkin, K. von Klitzing, and K. Ploog, Phys. Rev. B **42**, 5744 (1990).