Electron-Hole Recombination in GaAs: Si Superlattices in High Magnetic Fields

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Photoluminescence in magnetic fields up to 30 Teslas was used to study GaAs periodically doped with sheets of Si. The photoluminescence displays a broad band due to the recombination of photoexcited holes with electrons within the Fermi sea, which splits into a weak Landau level structure when a magnetic field is applied perpendicular to the layers. It is found that the lifetime of the photoexcited holes become longer when the doping period is made larger, which is a consequence of the increasing strength of the periodic self-consistent potential.

I. Introduction

Periodically doped semiconductors in which the donor atoms are placed in equally spaced planes of the host crystal lattice ($\delta-$superlattices) have attracted a great deal of attention recently due to their device applications[1] and as a source of basic research. In these systems, the carriers released from the donors are confined by a self–consistent periodic potential in one dimension, and their energy spectrum is characterized by minibands. Early studies have established the basic properties of $\delta-$doped structures using magneto-transport and optical measurements in zero magnetic field[2−6]. The photoluminescence (PL) of $\delta-$superlattices in zero magnetic field displays a broad emission band with a cut-off energy above the bandgap of the host crystal[3], and this is well explained in terms of optical transitions between the electrons confined by the superlattice potential and holes[7]. However, optical experiments in high magnetic fields have not been widely used to probe these structures, and this is probably due to the large broadening of the electronic levels due to the Coulomb scattering by the ionized donors[8−10], which prevents the splitting of the emission band into a Landau level structure. In this paper we present the first detailed measurements of the electronic states in periodically $\delta-$doped structures using photoluminescence techniques in fields of up to 30 Teslas.

II. Experimental

We studied GaAs samples with a planar doping of Si. The superlattices consisted of 100 periods. The samples studied are listed in Table I; the growth details for these samples are given in Ref. [11]. The PL response was measured using a pulsed diode laser operating at 1.575 eV, pulse rate of 20 MHz, and pulse length 0.3-0.5 ns. The low optical energy of the incident light pulses ($< 10^{15}$ J/pulse per mm^2) does not change significantly the electron density ($\Delta n < 10^7$ cm^{-2}). Optical fibers and time–correlated photon counting technique were used to time–resolve the PL, with a resolution of <100 ps [12]. The spectral resolution was limited to 0.3 meV, although smaller resolutions did not reveal any additional structure other than reported here. As a source of magnetic field for the high field measurements, the MIT Francis Bitter National Magnet Labo-

Table I. Description of the samples studied. The carrier density per superlattice period, the quantum mobilities, and the energy gap (Δ_{12}) between the $E1$ and $E2$ minibands were obtained from the analysis of the Shubnikov–de Haas spectrum.

Sample	SL period (Å)	Carrier density (cm^{-2})	Quantum mobility $E1$ (m^2/Vs)	Quantum mobility $E2$ (m^2/Vs)	Δ_{12} (eV)
No.1	220	2.0×10^{12}	0.130	0.304	0.023
No.2	110	2.1×10^{12}	0.134	—	—

ratory hybrid magnet facilities were used, which allowed to achieve fields of up to 30 Teslas.

III. Results

Before discussing the time response of the PL we present the time-averaged PL results. Fig. 1 shows the PL spectrum for sample No.1 as a function of the magnetic field. As the field is increased, we can see that the broad emission seen at B=0 develops a fine structure, which is due to the resolution of Landau levels. The emission has a cut-off at the Fermi energy, and the emission due to a given Landau level fades out as this Landau level crosses the Fermi energy. Fig. 2 shows the intensity of the luminescence around the Fermi energy (1.533 eV) as a function of the magnetic field. Also shown in Fig. 2 is the Shubnikov–de Haas effect for the same sample in 0–14 Tesla fields. The Shubnikov–de Haas oscillations seen in Fig. 2 are dominated by the electrons in the $E2$ miniband, which have a much higher quantum mobility than the electrons in the $E1$ miniband (see Table I). Fig. 2 shows that the Shubnikov–de Haas oscillations and the oscillations of the PL intensity at the Fermi energy are concomitant; moreover, Fourier analysis shows that the inverse field frequency of these oscillations is the same, thus demonstrating that the structure developed in the PL as a function of the magnetic field is due to the formation of Landau levels in the $E2$ miniband. Fig. 3 shows the peak positions detected in the PL spectrum of sample No.1 as a function of the magnetic field intensity. The peaks identified as belonging to the Landau levels structure are shown by solid circles. Extrapolation of the measured peak positions to B=0 establishes that the onset of the optical recombination of the photoexcited hole with electrons in the $E2$ miniband occurs at an energy of 1.511 eV in the zero-field PL spectrum. Assuming this value for the threshold of the $E2$ miniband, the position of the Fermi level as a function of the magnetic field can be calculated self–consistently if we use the sample parameters given in Table I. The quantum mobilities of the electrons in the $E1$ and $E2$ minibands were used as broadening parameters, and the calculated position of the Fermi level as a function of the magnetic field is shown in Fig. 3 by the thick line. Also shown in Fig. 3 by thin lines is the fan diagram for the Landau levels of the $E1$ and $E2$ minibands. We can see that at lower fields the structure seen in PL is in satisfactory agreement with the estimated positions of the Landau levels of the $E2$ minibands. Above ~15 Teslas, the quantum limit is achieved for the $E2$ miniband, and the single remaining peak seen in the PL spectrum follows the Fermi energy position.

With the carrier density of the sample obtained from the Shubnikov–de Haas oscillations given in Table I and the energy onset of the recombinations of the photoexcited hole with the $E2$ electrons obtained from the magnetophotoluminescence, the theoretical PL spectrum in zero magnetic field can be calculated according to the prescription described in Ref. [7], and the final results are shown in Fig. 4. It can be seen that theory reproduces quite well the main features seen experimentally, apart from the structure detected at 1.492 eV, which is due to an impurity related electronic transition in the host GaAs crystal. However, it should be noted that the main features are dominated by the recombinations with the electrons confined by the superlattice self–consistent potential, and are seen at an energy higher than the bandgap of the host crystal (1.519 eV).

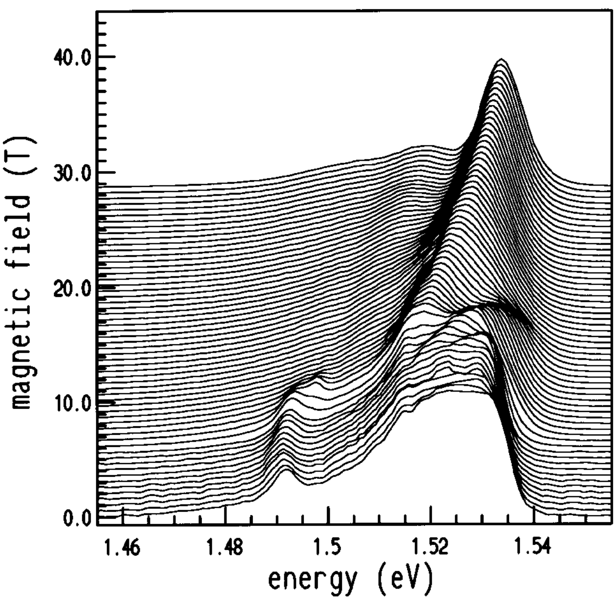

Figure 1. Intensity of the photoluminescence for sample No.1 as a function of magnetic field. The intensity of the magnetic field corresponding to each curve is obtained by following the spectrum base line to the scale on the left-hand side.

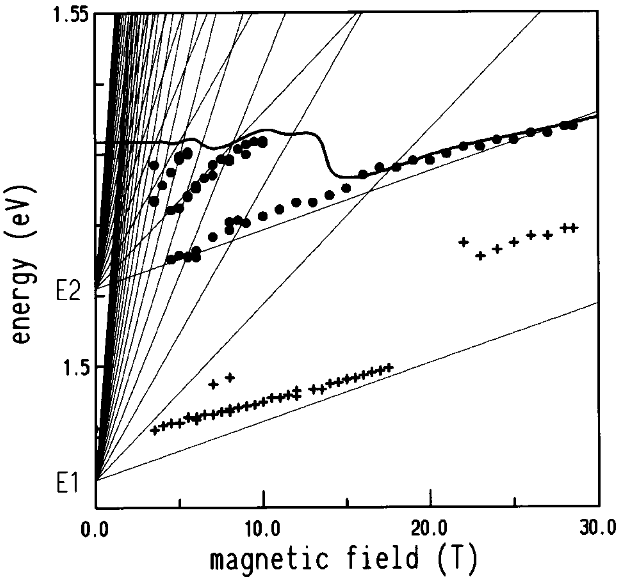

Figure 3. Solid circles and crosses represent the energy of the peaks seen in the magnetophotoluminescence of sample No.1. The solid circles are identified as being due to the recombination of the photoexcited hole with the electrons in the Landau levels. The thick curve is the calculated magnetic field dependent position of the Fermi energy. Thin lines represent the fan diagram of the Landau levels.

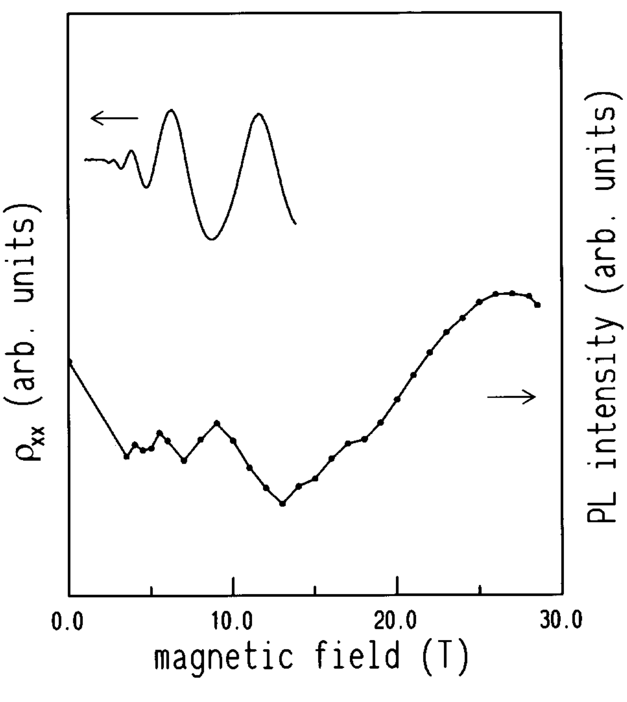

Figure 2. Intensity of the photoluminescence at 1.533 eV (approximately equal to the Fermi energy) (solid circles), and Shubnikov–de Haas oscillations in perpendicular fields up to 14 Tesla for sample No.1.

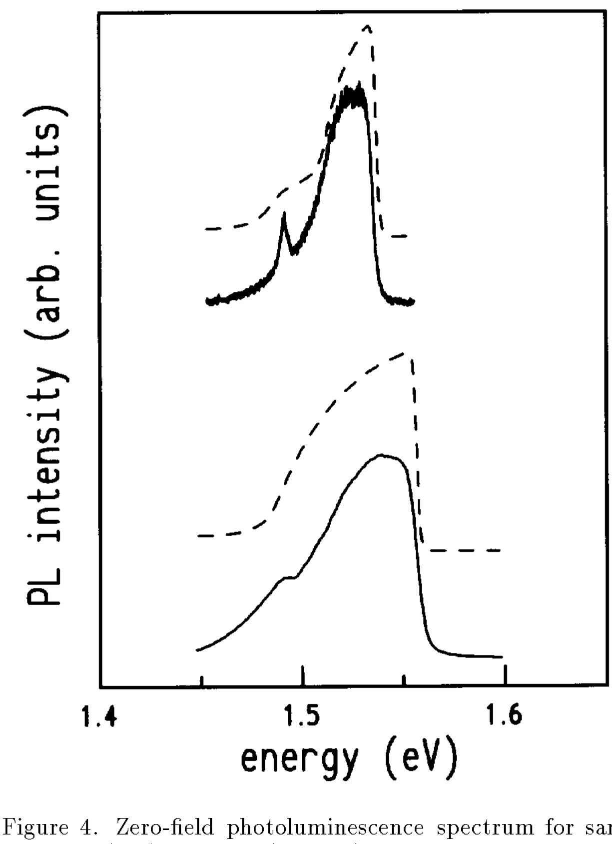

Figure 4. Zero-field photoluminescence spectrum for samples No.1 (top) and No.2 (bottom). The dashed curve represents the theoretical PL spectra, which were obtained with no adjustable parameters.

The time-resolved photoluminescence spectrum is shown in Fig. 5 for sample No.1 at the energy of 1.522 eV, which coincides with the most intense photoluminescence energy region. The solid curve was obtained by a deconvolution of the laser pulse from the PL spectrum of the sample assuming a single exponential decay; the relaxation time obtained is 0.26 nsec. We observed also that for photon energies around the peak position of the luminescence the relaxation time did not vary within an error of 0.01 nsec. For sample No.2, the luminescence at the energy 1.551 eV is described by a relaxation time of 0.18 nsec. This is slightly shorter than for sample No.1 because of the higher overlap of the hole and the electron wave functions due to the shorter superlattice period. The observed ratio of the lifetimes for sample No.1 and No.2 is 1.4, whereas the theoretical estimate is 1.2.

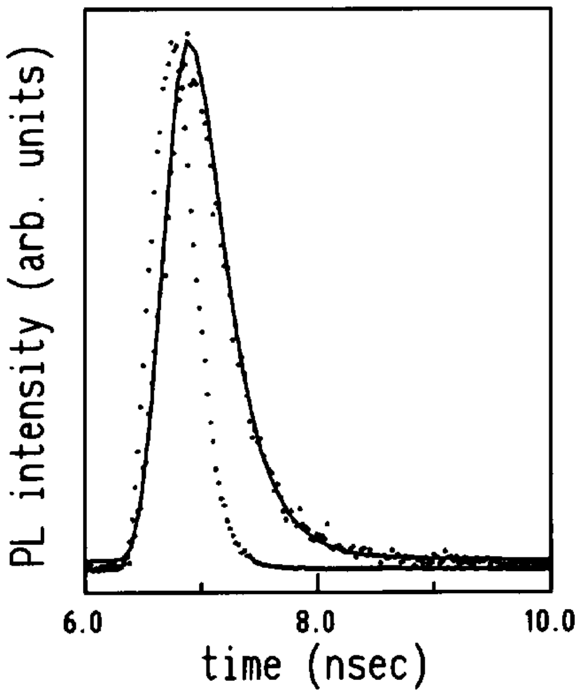

Figure 5. Evolution with time of the photoluminescence for sample No.1. The narrower peak corresponds to a laser pulse, and the broader one to the PL response of the sample at a photon energy of 1.522 eV. The solid curve is the deconvoluted PL response which gives a single exponential decay time of 0.26 nsec.

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