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Quantum oscillations of the luminescence from a modulation-doped GaAs/InGaAs/GaAlAs quantum well

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Magnetospectroscopic studies of a modulation-doped GaAs/InGaAs/GaAlAs quantum well (QW) are presented. Oscillations of the photoluminescence (PL) intensity in magnetic field are investigated. Recombination processes giving rise to the PL are identified and their effect on the PL is established. It is shown how measurements of the oscillations can provide information on the density of the quasi-two-dimensional electron gas confined in the QW. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2171487]

Pseudomorphic modulation-doped GaAs/InGaAs/AlGaAs quantum wells (QWs) have become standard systems used in high-speed electronics.[1] Quite recently a new application of high mobility transistors based on pseudomorphic QWs has been proposed as emitters of terahertz radiation.[2] Due to a large conduction band offset, the pseudomorphic QWs can accommodate high density of two-dimensional electron gas (2DEG), which is crucial for high performance devices. The density of the 2DEG confined in a QW can be established by electrical methods. Standard Hall-effect measurements give an effective Hall density which is a function of the 2DEG density and (if present) the density of carriers in parallel current paths.[3] The density of the 2DEG may be determined from the frequency of Shubnikov–de-Haas (SdH) oscillations (f_{SdH}) of longitudinal resistivity in magnetic field.[4] Optical methods, which do not require any fabrication of a sample nor contact formation, can also be applied. It has been shown that the density can be found from a linewidth of low-temperature photoluminescence (PL)[5–7] peak or from measurements of optical SdH oscillations of the PL intensity at the Fermi energy.[8] In this letter we report on another approach, based on measurements of the PL intensity monitored at constant detection energies in magnetic field.[9,10] We show that in the low-energy tail of the spectrum pronounced dips in the PL intensity occur in magnetic fields around even filling factors. These features appear with the frequency f_{SdH}. We propose to use this effect as a method for determination of the 2DEG density in a modulation-doped pseudomorphic QW.

The investigated structure was grown by molecular beam epitaxy. It consisted of a 750 nm GaAs buffer layer, followed by 100 nm of a short period (5 nm $\mathrm{Al_{0.2}Ga_{0.8}As}$/5 nm GaAs) superlattice, a 310 nm of $\mathrm{Al_{0.2}Ga_{0.8}As}$ back barrier, an 11 nm $\mathrm{In_{0.2}Ga_{0.8}As}$ QW, and a 205 nm GaAs top barrier. The Si δ doping ($n_D=1.5\cdot 10^{12}\ \mathrm{cm^{-2}}$) was positioned 10 nm from the QW in the back $\mathrm{Al_{0.2}Ga_{0.8}As}$ barrier. A similar δ doping was introduced 5 nm below the structure surface to saturate surface states. The PL measurements were performed in magnetic field up to 5 T in Faraday configuration. The same optical fiber was used both for laser excitation ($\mathrm{Ar^+}$ ion laser, $\lambda=514.5$ nm) and collection of emitted light. The sample was immersed in liquid helium and mounted in close proximity to the end of the fiber. The collected light was dispersed by a monochromator and focused on a N_2 gas cooled InGaAs photomultiplier. Standard lock-in techniques were used for data acquisition.

The PL spectrum from the sample measured without magnetic field at $T=4.2$ K is shown in Fig. 1. The spectrum peaks at energy $E_0=1.204$ eV. Four energy ranges with characteristic energies: $E_A=1.2915$ eV, $E_B=1.2652$ eV, $E_C=1.2276$ eV, $E_D=1.1922$ eV, and $E_E=1.1697$ eV (see arrows in Fig. 1) can be distinguished in the spectrum. The most energetic part of the spectrum ($E_B<E<E_A$) results from the recombination of free electrons and free holes.[11,12] The main radiative-recombination channel in the energy range $E_0<E<E_B$ is the recombination of free electrons and bound holes.[11–13] A decisive role of alloy composition fluctuations for the localization of holes involved in the process has recently been shown.[14] In the energy range of $E_0<E<E_C$ an additional process with emission of LO phonon be-

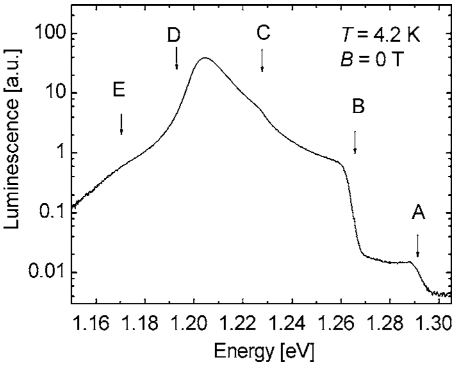

FIG. 1. Photoluminescence spectrum of the modulation-doped GaAs/InGaAs/AlGaAs QW with a high density 2DEG measured at $T=4.2$ K in magnetic field $B=0$ T. Characteristic energies are marked with arrows.

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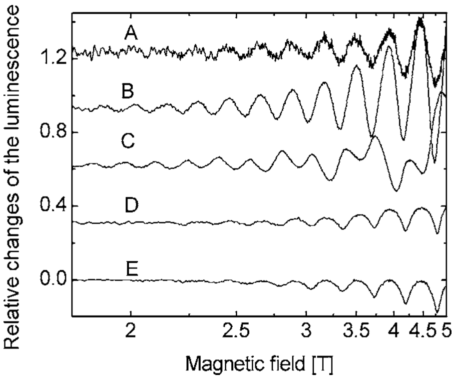

FIG. 2. Relative changes of the PL intensity $[I(B)/I(1\ \mathrm{T})]$ from the QW with a high density 2DEG measured at $T=4.2$ K at characteristic energies. Linear background has been subtracted and offset has been added for more clarity.

comes possible.[6,15] Finally recombination events involving scattering from ionized impurities in the barrier are responsible for the broadening of the PL spectrum and its low-energy tail $(E<E_0)$.

The QW PL spectrum evolves into a series of peaks in magnetic field. The peaks are characteristic for Landau level (LL) quantization of the 2D density of states. The separation of peaks in the main part of the spectrum $(E_0<E<E_B)$ is smaller than at higher energies $(E_B<E<E_A)$. Different energy separations are due to different processes involved: cyclotron resonance energies in the former and latter energy ranges are equal to the electron cyclotron energy $(\hbar\omega_C^*=\hbar\omega_c^e)$ and to the sum of electron and hole cyclotron energies $(\hbar\omega_C^*=\hbar\omega_c^e+\hbar\omega_c^h)$, respectively. In this work we focus our attention on oscillations of the PL intensity in magnetic field. The magnetic-field evolution of the PL intensity at characteristic energies E_i is shown in Fig. 2.

Density of states of the 2DEG at fixed energy E oscillates as a function of $1/B$. The density has a peak value each time a LL position becomes resonant with the energy. In a simple model of a parabolic band, the frequency of those oscillations f can be related to the energy E with the following relation:

$$f=(E-E_g^*)\frac{m^*}{\hbar e}, \tag{1}$$

where m^* stands for the electron mass (a sum of electron and hole masses) for the free-to-bound (free-to-free) recombination and E_g^* stands for the effective band gap in the QW. The energy E_g^* equals E_g—the band gap energy for free-to-free recombination or E_g-E_b (with the hole localization energy E_b) for the free-to-bound recombination. In particular, when observed at Fermi level energy, the density of states oscillates with the frequency f_{SdH}, which can be related to a density of 2DEG in the QW: n_s by the formula $f_{\mathrm{SdH}}=n_S h/2e$. To examine the dependence of the frequency f on the detection energy we have applied the fast Fourier transform (FFT) in a $1/B$ domain to the PL intensity versus magnetic field traces and the resulting power spectra are shown in Fig. 3. As can be seen, the same frequency $f_{\mathrm{SdH}}=33.2$ T, corresponding to the 2DEG density of $1.60\cdot 10^{12}\ \mathrm{cm}^{-2}$, can be observed at the energies E_i. This value agrees with the concentration of intentional doping, which points to the QW as a main conduction channel, however for unambiguous identification of possible parallel conducting layers temperature-dependent Hall-effect measurements may be performed.

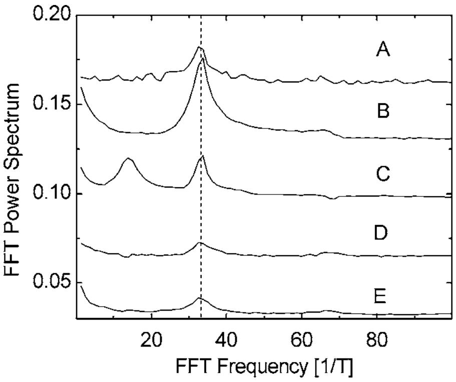

FIG. 3. A fast Fourier transform power spectrum of the relative changes of the PL intensity in magnetic field. Dashed line corresponds to the frequency of SdH oscillations. Offset is added for clarity.

Oscillations of the PL intensity, which occur with the frequency f_{SdH}, can be related to the oscillations of a density of states at the Fermi level in the following way. The emission at the energy E_A results from recombination of free electrons close to the Fermi level and free holes. The recombination of electrons close to the Fermi level and bound holes gives rise mainly to the emission at the energy E_B (although much weaker free-to-free recombination is also present). The PL-intensity oscillations at the energy E_C are the superposition of oscillations with two frequencies $f=14$ T and f_{SdH}. The former frequency corresponds to oscillations of density of states for the free-to-bound recombination at the energy E_C [compare Eq. (1)]. The latter frequency reflects the oscillations of density of states at the Fermi level and it is present in the spectrum due to the LO-phonon assisted recombination of electrons from the Fermi level and bound holes, observed at the energy E_C.

The results of the FFT analysis of spectra corresponding to measurements at several detection energies are summarized in Fig. 4. Three dashed lines in Fig. 4 represent three theoretical dependencies expected for the free-to-free (f.f.), free-to-bound (f.b), and LO-phonon-assisted-free-to-bound recombination (LO-f.b.) obtained with numerical values of $E_g=1.209$ eV, $E_b=7$ meV, $m_e^*=0.064m_0$, and $m_h^*=0.19m_0$ taken from Ref. 12. The main optical recombination process

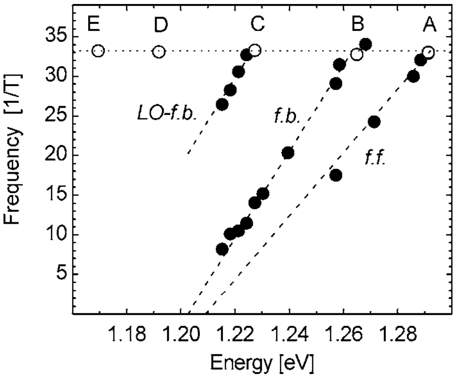

FIG. 4. Dependence of the frequencies of the PL oscillations on the detection energy. Dashed lines correspond to theoretical dependences for three processes: the recombination of free electrons and free holes (f.f.); free electrons and bound holes (f.b.), and LO-phonon assisted recombination of free electrons and bound holes (LO-f.b.). Open circles correspond to frequencies measured at characteristic energies of the spectrum.

in our experimental conditions (defined by temperature and excitation intensity) is the free-to-bound recombination. As a result, the corresponding frequency of oscillations can be detected at energy $E_0 < E < E_B$. Additionally the frequency related to the LO-phonon-assisted-free-to-bound recombination can be detected at $E_0 < E < E_C$. The intensity of the free-to-free recombination is relatively weak and corresponding oscillations can only be detected in highest energy range ($E_B < E < E_A$). However, it may be expected that at higher temperature or with higher excitation power density the frequency resulting from the free-to-free process will be present in the PL-intensity oscillations in the whole energy range. A possible presence of three periods of oscillations in highly doped pseudomorphic QWs also means that great care must be taken when analyzing and attributing the oscillations of the PL intensity.

Optically detected quantum oscillations have previously been proposed as a method of investigation of pseudomorphic QWs with a high density 2DEG.[9,10] A new result presented in this letter relates to intensity oscillations in the low-energy tail of the PL from such a QW. As can be seen in Fig. 2, pronounced dips in the PL intensity observed at energy E_D or E_E occur in magnetic fields around even LL filling factors. Similar behavior has previously been observed in the PL from a QW with a high electron density purposely doped with acceptors.[16] The effect was explained in terms of filling-factor-dependent oscillations of the efficiency of screening the localizing acceptor potential by the 2DEG. If it is assumed that the radiative recombination from the QW is much less effective than the nonradiative process, then the total PL intensity can be related to the radiative recombination rate. In the case of a ground state of a valence hole bound to an acceptor, the rate is proportional to the mean area of the bound hole state.[16] That area is affected by the screening of the acceptor potential by the 2DEG in the QW. The screening becomes less effective in magnetic fields, at which the Fermi energy is midway between the LLs (at even filling factors). This results in dips in the PL from the QW, which occur with the frequency f_{SdH}. The presence of such oscillations in the low-energy PL tail confirms that this emission results from a broadening of the PL due to free-to-bound recombination. The same mechanism is responsible for oscillations in a total integrated intensity of the QW PL, shown elsewhere.[17] Observation of the dips in the low-energy tail of the emission from the QW in magnetic field provides a simple method for determining the 2DEG density. The frequency of their appearance does not depend on detection energy ($E < E_0$) in a relatively broad energy range. It can also be applied to all pseudomorphic QWs with high 2DEG density, as the localization of holes is their characteristic property.

In conclusion, we have presented the results of a magnetospectroscopic study of a pseudomorphic GaAs/InGaAs/AlGaAs QW with a high density 2DEG. We have shown that the intensity of the PL from the QW is influenced by oscillations of density of states corresponding to the detection energy and by the oscillations of density of states at the Fermi level. We have shown that the latter effect results in pronounced dips in the low-energy tail of the PL from the QW. We have proposed this effect as a method of determination of the 2DEG density in a modulation-doped pseudomorphic QW.

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