Manifestation of the cyclotron mode in hot-magnetoluminescence and Raman spectra in a single GaAs/AlGaAs heterojunction

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An emission line shifted from the laser line by the electron cyclotron energy was observed in a single GaAs/AlGaAs heterojunction and investigated. It was shown that, together with a Raman signal from two-dimensional electrons, a line which has similar properties and which arises as a result of the recombination of hot volume electrons and heavy holes predominates in the spectrum. This conclusion follows from analysis of the magneto-oscillations of the intensity of this line. © *1995 American Institute of Physics.*

1. The properties of two-dimensional (2D) charge layers in various semiconductor structures have attrracted the attention of investigators for a long time. The great diversity of the fundamental effects in such systems makes it necessary to use different methods of measurement. In the last few years investigations of 2D systems by means of Raman scattering spectroscopy (RSS) have increased substantially.[1] This method has been used to measure the characteristic energies of 2D systems — intersubband splittings, cyclotron energy and energy of the roton minimum in the magnetoplasmon dispersion, spin splitting, and gap under the conditions of the fractional quantum Hall effect.[1,2] The most perfect single GaAs/AlGaAs heterojunctions (SHJ) or quantum wells were employed for these measurements, and the RSS measurements are performed, as a rule, under resonance conditions, specifically, when the energy E_L of the pump photon or E_S of the scattered photon is equal to the energy of the real state. Under such conditions the question of separating the resonance RSS signal from the signal due to hot magnetoluminescence (HML) of photoexcited carriers from the 2D channel and the volume of GaAs is nontrivial.[3] This question has still not been studied systematically, and the signals were separated on the basis of the assumptions that the spectral position of the HML lines in a fixed magnetic field H is also fixed and does not depend on E_L and that the RSS signal follows E_L. It will be shown below that this simple criterion does not work in the case of high-quality heterostructures.

In the present study we have experimentally separated different effects which occur in SHJ under the conditions of resonance photoexcitation and which give rise to coinciding lines in the luminescence spectra. We have also studied HML of photoexcited carriers in GaAs.

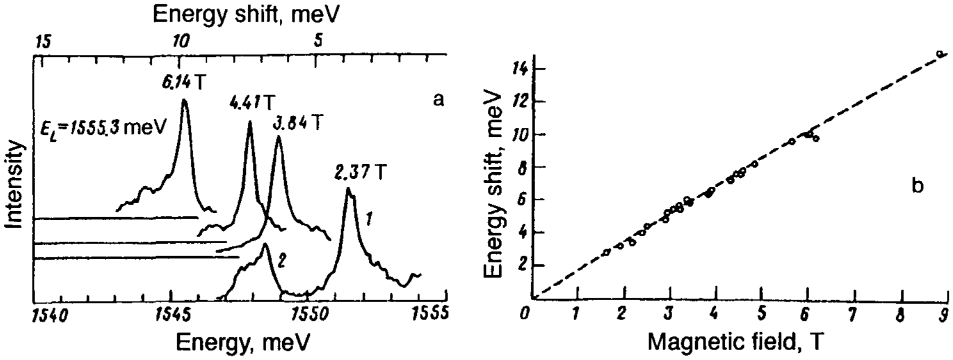

FIG. 1. a — Emission spectra measured for different values of H and pump photon energy $E_L = 1555.3$ meV. b — Energy shift of the line as a function of the magnetic field. The dashed line indicates the approximation corresponding to measurements of the electron cyclotron resonance in GaAs (see text).

2. We investigated several high-quality GaAs/AlGaAs SHJ [with electron mobility $(2-3)\times 10^6$ cm^{-2}/(V·s) and concentration $(0.8-1.1)\times 10^{11}$ cm^{-2}] with 60- and 2000-nm-thick AlGaAs spacer and GaAs buffer layers, respectively. Photoexcitation was performed with a tunable Ti/Sp laser in the range 1530–1580 meV. The spectral unit was a Ramanor U-1000 double monochromator. All measurements were performed at a temperature of 4.2 K. The high quality of the samples was confirmed by the very narrow width of the experimental lines (0.2 meV) and resonances (0.05 meV).

3. A series of spectra measured in different magnetic fields (oriented close to the normal direction) with resonance excitation is shown in Fig. 1a. All spectra contain two lines — 1 and 2 (in Fig. 1a the second line is presented, for clarity, only for $H=2.37$ T) — shifted from the laser line by energy δ and 2δ, respectively. The energy δ is determined only by the magnitude of the magnetic field, and its dependence on H is shown in Fig. 1b. The dashed line represents an approximation of the magnetic field dependence of the electron cyclotron energy $\hbar\omega_C$ (taking into account the nonparabolicity of the conduction band) obtained in cyclotron resonance experiments:[4] $\hbar\omega_c = 1.766H - 0.008H^2$. It is evident that our experimental data agree well with this dependence, which corresponds to the electron cyclotron mass $m_c = 0.066m_0$.

The spectral position of the line 1 measured as a function of E_L with $H=6.02$ T is shown in Fig. 2a. As one can see from this figure, the spectral position of the experimental line follows the energy of the pump photon and always corresponds to a spectral shift by $\hbar\omega_c$ from E_L. We note that a change in E_L with fixed H is accompanied by oscillations of the intensity of the line 1, which are shown in Fig. 2b. The properties of the line 1, shown in Fig. 2, at first glance indicate its Raman origin, but three alternative possible explanations of the nature of this line can generally be discussed: a) Raman scattering by electrons in the 2D channel, b) Raman scattering by photoexcited electrons in the volume of GaAs, and c) HML of photoexcited carriers. To choose between the 2D and 3D nature of the effect we employed a standard test — the change in the angle of inclination of H with respect to the interface. In this case $\hbar\omega_c$ of the 2D electrons should follow the component of H that is perpendicular to the interface. We found, however, that the

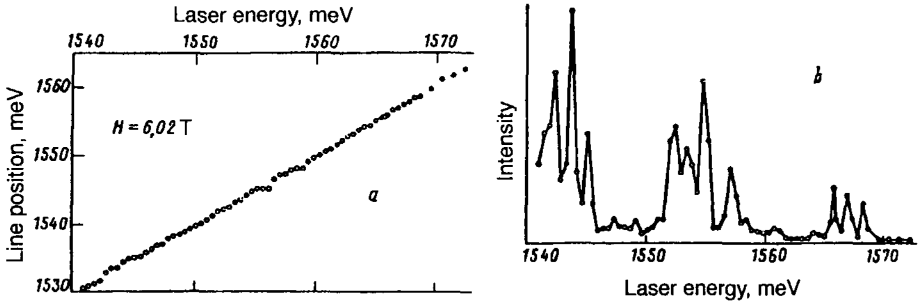

FIG. 2. Spectral position of the line (a) and its intensity (b) as a function of E_L for $H = 6.02$ T.

properties of the dominant line and the value of δ are nearly the same for all values of the angle. Moreover, we also discovered a much weaker line whose position depended on the angle and which we interpreted as Raman scattering by 2D electrons. The properties of this line will be investigated in a separate paper. Returning to line 1 which we are examining here, we conclude that it is of a 3D nature. Choosing between the above-mentioned variants *b*) and *c*), it can stated that in the case of Raman scattering by photoexcited carriers, the intensity of the line should be a quadratic function of the pump intensity, since the density of photoexcited carriers is proportional to the laser power. Since in the experiment the line intensity was found to depend linearly on the photoexcitation power, the effect which we investigated can be unequivocally identified as HML of photoexcited carriers in the volume of GaAs. We note that the observed properties of line 1 correspond completely to the characteristic indicators of Raman scattering, creating the illusion that resonance Raman scattering is being observed. To underscore the main difference between the HML which we discovered from the previously investigated luminescence (whose spectral position did not depend on E_L), we shall call it Raman-like HML (RLHML). The lines displaced from the laser line by δ and 2δ correspond to recombination of photoexcited holes with electrons which have relaxed in the process of cooling on the nearest and next-to-nearest Landau levels. The possibility of observing such a "ladder" of lines in the HML spectrum indicates that the experimental samples are of high quality, which has a consequence that the energy relaxation times of the photoexcited carriers are quite long. The experimental value of m_c, equal to the value of m_c of electrons in the volume of GaAs, indicates that we are investigating HML associated with the energy relaxation of a hot electron, while the hole relaxation time is much longer and a hole recombines from the same state in which it was created. We note that one of the optical transitions (either absorption or recombination) is dipole-forbidden ($\Delta n = N_e - N_h \neq 0, -2$), since the change in the quantum number N_e for an electron during relaxation is not accompanied by a corresponding change in the number N_h for a hole.[3]

To study the energy structure of the levels with which the RLHML is associated, it is possible to investigate the dependences of the type shown in Fig. 2b — scanning E_L with $H =$ const. However, we employed a different method — E_L was held constant, while H and the monochromator were scanned simultaneously, so that the spectral posi-

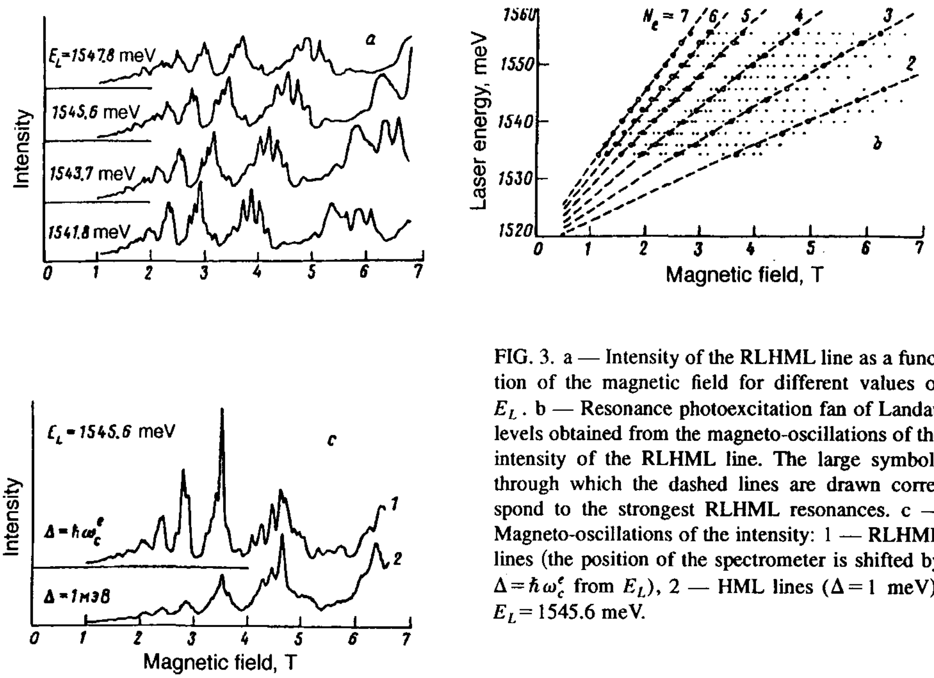

FIG. 3. a — Intensity of the RLHML line as a function of the magnetic field for different values of E_L. b — Resonance photoexcitation fan of Landau levels obtained from the magneto-oscillations of the intensity of the RLHML line. The large symbols through which the dashed lines are drawn correspond to the strongest RLHML resonances. c — Magneto-oscillations of the intensity: 1 — RLHML lines (the position of the spectrometer is shifted by $\Delta=\hbar\omega_c^e$ from E_L), 2 — HML lines ($\Delta=1$ meV); $E_L=1545.6$ meV.

tion of the monochromator slit was always shifted by the amount $\Delta=\hbar\omega_c$ from E_L in the direction of lower energies and the intensity of the line was measured as a function of H at the same time.

Figure 3a shows oscillations of the intensity of the RLHML line in a parallel magnetic field. These oscillations were measured by the method described above for different values of E_L. The oscillations have a rather complex shape. However, if E_L is varied in sufficiently small steps, then the genesis of each maximum can be followed and it can be determined uniquely for all E_L. After a series of such oscillations with different values of E_L was analyzed, we obtained the fan of the Landau levels which is shown in Fig. 3b. The lines in the fan are drawn for the strongest resonances, and the numbers on each line correspond to the number of the Landau level of the electrons. Approximating the positions of the main maxima shows that the splitting between the neighboring levels corresponds to the reduced cyclotron mass of an electron and a heavy hole. The presence of a large number of peaks in the oscillations is explained by the strong mixing of the wave functions of the heavy holes, which makes it possible to observe the forbidden transitions of the electrons and heavy holes (with $\Delta n\neq 0,-2$). This mixing is much weaker for light holes because of the large energy splitting of their levels, which results in a much stronger argument against the transitions with $\Delta n\neq 0,-2$. Consequently, such transitions are not manifested in the oscillations investigated by us. The participation of a heavy hole in the recombination process explains the quasi-Raman behavior of the RLHML line, which is always displaced by $\hbar\omega_c$ from the laser line: By varying E_L we systematically go through the different absorption resonances which are associated with different magnetic levels of a heavy hole, the splitting between which is small.

To compare our results with previous investigations of HML, we employed the method of measuring oscillations which is described in Ref. 5 . In this method, E_L was held constant, the position of the monochromator slit was fixed at a distance Δ from the laser and H was scanned. The splitting Δ from the laser line was chosen to be rather small — 1 meV. This method, in contrast to our method, makes it possible to observe recombination of carriers at the same levels at which they were created. It is therefore sensitive to the dipole-allowed transitions — the strongest peaks correspond to the creation and recombination of electrons and holes with $\Delta n = 0, -2$. The application of this method made it possible in Ref. 5 to measure the mass and g-factor of light holes, which were completely reproduced in our samples. In addition, we found that when H is oriented perpendicular to the interface, transitions with participation of light holes dominate in the oscillations. When H makes an angle with the interface, these transitions become weaker (supposedly because of the effect of the parallel component of the magnetic field on the relaxation of light holes located near an interface). When H is directed along the interface, transitions in which heavy holes participate predominate. This makes it possible for us to measure self-consistently in the same sample the masses of the electrons and the heavy and light holes, the anisotropy of these masses, and the contribution from the nonparabolicity of the bands and to determine all parameters of the band structure of GaAs. This subject requires a separate study.

The oscillations obtained by the two alternative methods for the case in which the position of E_L for method 1 coincides with the position of the monochromator slit for method 2 are compared in Fig. 3c. We see that the positions of the main resonances coincide, and the dipole-forbidden transitions are stronger for type-1 oscillations.

We separated experimentally the resonance Raman scattering and HML channels from one another. We also investigated magneto-optic oscillations of a new type — oscillations of the intensity of the recombination of hot electrons and heavy holes in the volume of GaAs — which gives us a tool for determining the parameters that describe the structure of the valence band of GaAs.

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