Anomalous temperature dependence of magnetooptic oscillations in the intensity of the recombination radiation of 2D electrons

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The temperature dependence of magnetooptic oscillations of a new type in a system of 2D electrons has been studied. An intersubband relaxation accelerates as the temperature is lowered. The initial and final spin states of the electrons involved in this relaxation are important.

1. Magnetooptic oscillations have been discovered in the intensity of the recombination of two-dimensional (2D) electrons.[1–3] This effect, which is an optical analog of Shubnikov–de Haas oscillations, has attracted considerable research interest because of its novelty, and also because it presents us with an alternative method for studying such fundamental phenomena in 2D systems as condensation into an incompressible Fermi liquid and Wigner crystallization. It was found in Ref. 2 that, in a case in which 2D electrons recombine with free holes, the sharp peaks in the intensity of the recombination radiation of the electrons of the first excited quantum-size subband, plotted as a function of the magnetic field, coincide exactly with the positions of integer filling factors of the 2D electron gas in the ground subband. A mechanism involving a screening of the Coulomb potential of photoexcited holes has been invoked in order to explain the observed effect. That mechanism has been used to explain the observed disappearance of the oscillations as the temperature is raised from 0.12 to 4.2 K. The behavior of the recombination rate corresponding to this mechanism was subsequently observed in time-resolved experiments.[4]

In Ref. 5 we studied the magnetooptic oscillations in the intensity of the recombination radiation of the 2D electrons from the first excited quantum-size subband with a nonequilibrium filling in the case of the recombination of a photoexcited hole bound at an acceptor (a neutral center). It was found there, in contrast with the results in Refs. 2 and 3, that these oscillations are not directly related to the filling factor in the ground subband or thus to the screening. We showed that the abrupt decreases observed in the intensity occur when Landau levels of the ground subband cross the zeroth Landau level of the excited subband. One possible mechanism for the occurrence of these abrupt decreases is an elastic relaxation of nonequilibrium carriers at the time of level crossing. The mechanism for the intersubband relaxation in the intervals between level crossings was not clearly resolved in Ref. 5. In the present letter we are reporting a study of the temperature dependence of the probability for this relaxation.

2. We studied the intensity of the recombination radiation from the first excited quantum-size subband with a nonequilibrium filling in a single GaAs–AlGaAs heterojunction during continuous photoexcitation. The 2D electrons recombined with photoexcited holes bound at acceptors in a δ-dope layer 300 Å from the interface. To study the temperature dependence, we used a device which pumped off the liquid ^{3}He, so that temperatures over the range 40–0.4 K could be reached. The experimental apparatus is described in more detail in Ref. 5.

3. Figure 1 shows spectra of the recombination radiation measured at two temperatures, $T = 4.2$ and 0.4 K, for magnetic fields (a) $H = 6.5$ T and (b) $H = 8.8$ T. The arrows mark the line of the excited subband. We see that the intensity of this line behaves in completely different ways as a function of the temperature in the different magnetic fields. While the line intensifies in case *a* as the temperature is lowered, it disappears in case *b*. This result is illustrated by Fig. 2a, which shows the integral intensity of the line of the recombination radiation of the excited subband as a function

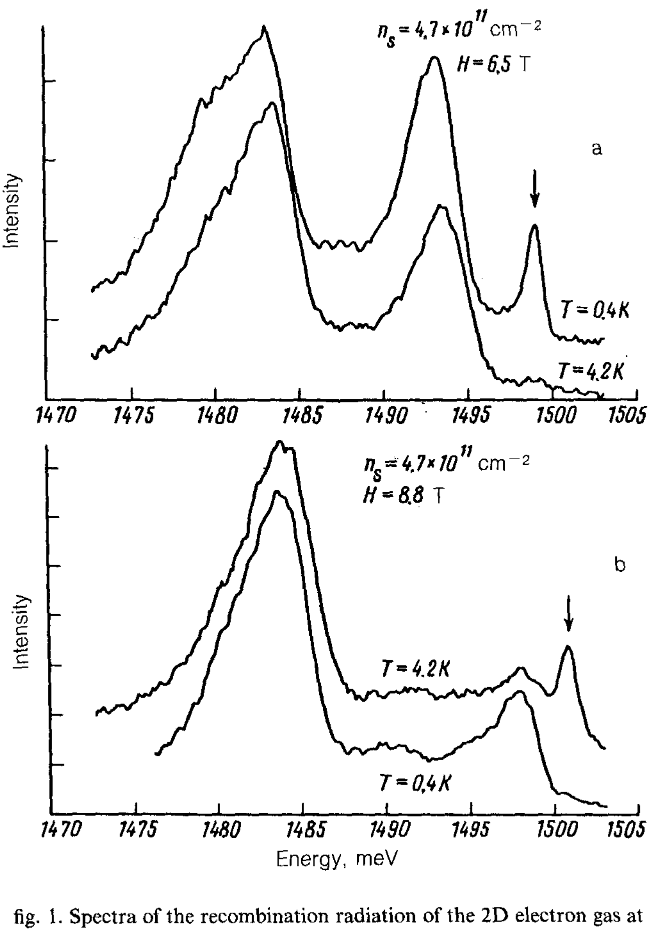

fig. 1. Spectra of the recombination radiation of the 2D electron gas at $T = 4.2$ and 0.4 K for two values of the perpendicular magnetic field. a—$H = 6.5$ T; b—$H = 8.8$ T. The arrows mark the recombination line corresponding to the excited subband.

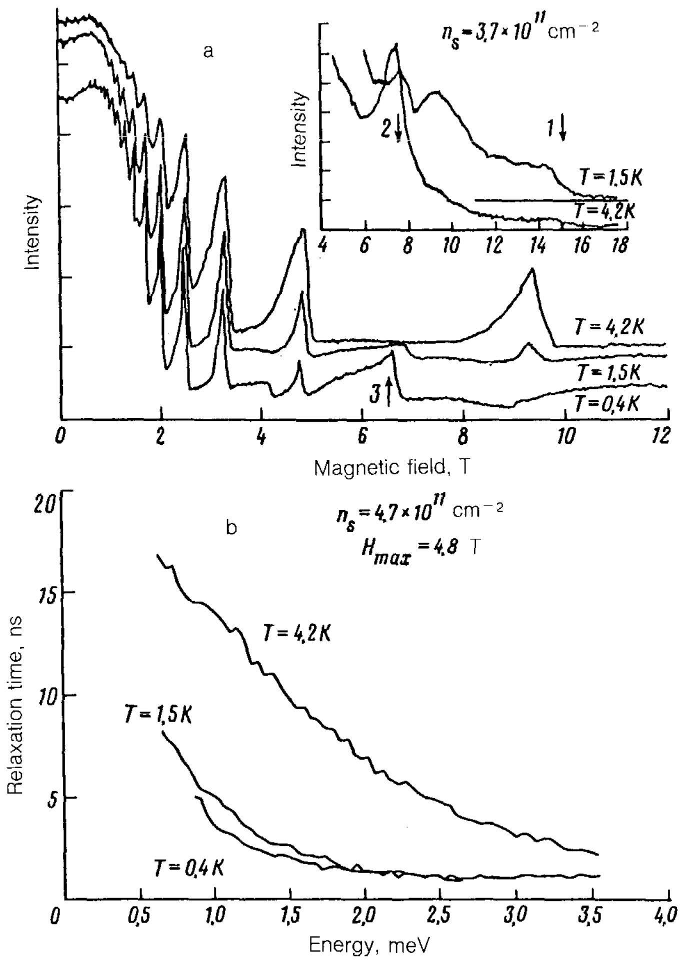

FIG. 2. a: Integral intensity of the recombination radiation of the excited subband, I_1, versus the magnetic field at $T = 4.2$, 1.5, and 0.4 K ($n_s = 4.7\times10^{11}$ cm^{-2}). The inset shows the same results near the filling factor $\nu = 1$ for $n_s = 3.7\times10^{11}$ cm^{-2}. The arrows mark the integer filling factors. b: Intersubband relaxation time versus the energy gap between the zeroth Landau level of the excited subband and the second Landau level of the ground subband according to a calculation from the shape of the $I_1(H)$ peak near $H = 4.8$ T.

of the magnetic field for three temperatures. The intensities of the main peaks which exist at $T = 4.2$ K decrease with decreasing temperature. The peak corresponding to the crossing of the zeroth Landau level of the excited subband and the first Landau level of the ground subband disappears completely. At the same time, some additional peaks appear near odd filling factors, $\nu = 3$ and 5, as the temperature is lowered. These additional peaks shrink sharply when the filling factor becomes less than an odd integer. The inset in Fig. 2a shows the same results as in Fig. 2a, near the filling factor $\nu = 1$ for $T = 4.2$ and 1.5 K. We see that at a high temperature the intensity of the line of the excited subband is zero in this region (all the electrons of the ground subband are in the zeroth Landau level; the energy gap for relaxation from the excited subband is equal to the energy of the intersubband splitting and is independent of the magnetic field). As the temperature is lowered, the intensity of this line is not zero at $2>\nu>1$, while it drops abruptly to zero at $\nu<1$.

The appearance of additional peaks near odd filling factors as the temperature is lowered can be attributed to an increase in the spin splitting. Specifically, under the assumption that a relaxation without spin flip should be faster than one with spin flip, we would have $g\mu H<kT$ in the case $T=4.2$ K, where μ is the Bohr magneton, and $g=-0.44$ is the effective electron g-factor in GaAs ($g\mu H=1.8$ K in a field of 6 T). Consequently, at this temperature, the two spin sublevels in the ground subband are filled roughly equally near odd values of the filling factors. In other words, vacancies for relaxation exist at both spin sublevels, and a fast intersubband relaxation is possible for both spin directions in the excited subband. As the temperature is lowered to $T=0.4$ K, we have $g\mu H>kT$. A substantial difference arises between the populations of the spin sublevels in the ground subband. This difference leads in turn to an effective increase in the spin splitting, because of a strengthening of the exchange interaction. Near odd filling factors, vacancies therefore exist only in the upper sublevel of the ground subband, and an effective relaxation can occur only for electrons from the upper spin sublevel of the excited subband. The relaxation of electrons from the lower spin sublevel is slowed significantly; as a result, the intensity increases, as is observed experimentally. When the filling factor becomes smaller than these odd values, vacancies for relaxation appear in the lower spin sublevel also, and the intensity abruptly drops to zero.

Figure 3 shows the temperature dependence of the intensity of the line of the excited subband near the crests of the main peaks, at $H=4.8$ and 9.3 T, and also near

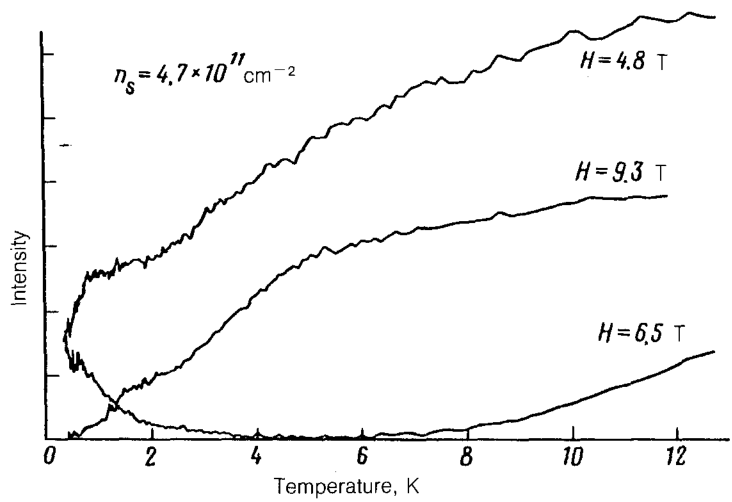

FIG. 3. Integral intensity of the recombination radiation of the excited subband, I_1, versus the temperature at the main peaks, $H=4.8$ and 9.3 T, and also at the additional peak, $H=6.5$ T.

the additional peak at 6.5 T. Near this peak at $H = 6.5$ T, the dependence is a thermal-activation dependence at $T > 5$ K. The thermal-activation gap is 5 meV, in good agreement with the energy separation of the zeroth Landau level of the excited subband and the first Landau level of the ground subband at $H = 6.5$ T, as found from the recombination spectrum. At $T < 5$K, the dependence is not of a thermal-activation nature in any case, and the behavior of the intensity for the main peaks is determined by the temperature dependence of the relaxation matrix element. We wish to stress that the shape of the intensity oscillations near the main peaks as the magnetic field is varied is determined by specifically the relaxation, rather than by thermal activation from the ground subband to the excited subband. Support for this assertion comes from the fact that estimates of the electron-gas temperature required to explain the observed shape of the oscillations yield values far greater than the actual temperature. In particular, for $T = 4.2$ K and at the intensities of the optical pumping used in these experiments, the heating of the electron system is a matter of several tenths of a degree,[6] while the temperature estimated from the shape of the oscillations, as mentioned above, is about 10 K. Further proof that the observed shape of the oscillations is determined by intersubband relaxation comes from the time-resolved experiments of Ref. 7. If the observed intensity of the line were determined by thermal activation, the population of the excited subband would not vary in time, and the spectra recorded at different delays after the pump pulse would have the same shape. Actually, it was found that the line corresponding to recombination from the excited subband after the laser pulse disappeared much more rapidly than the line of the ground subband. This difference can naturally be linked with intersubband relaxation.

It follows from Fig. 3 that the mechanism responsible for the intersubband relaxation in the intervals between level crossings is an anomalous temperature dependence; specifically, the relaxation accelerates with decreasing temperature. Knowing the recombination time in the excited subband for our system,[7] $\tau_{\rm rec} = 30$ ns, and assuming that the population of the excited subband is determined exclusively by recombination and intersubband relaxation, we can relate the observed intensity to the relaxation time by the obvious equation

$$I_1 = I_1^* / 1 + (\tau_{rec}/\tau_{rel}),$$

where I_1^* is the intensity in the absence of relaxation, which we can estimate as the intensity in a zero magnetic field. We then find an expression for the relaxation time:

$$\tau_{rel} = \tau_{rec} / (I_1^*/I) - 1 .$$

The dependence of $\tau_{\rm rel}$ on the energy separation of the levels calculated in this manner is shown in Fig. 2b for three temperatures.

In summary, this study has resulted in the observation of an anomalous temperature dependence of a new type for the magnetooptic oscillations in the intensity of the recombination radiation of 2D electrons. This dependence cannot be explained on the basis of a screening mechanism. We have shown that the spin orientation of the 2D electron in the initial and final states is important for a description of these oscillations in terms of an intersubband relaxation. A question which remains open is the mechanism for the intersubband relaxation. This mechanism should result in an acceleration of the relaxation with decreasing temperature.

We also note that since the intensity of the excited-subband line at low temperatures near odd values of the filling factor is sensitive to the spin orientation of the electrons, we have a method for the optical detection of electron spin resonance in an excited subband.

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