Magnetooptics of quasi-1D electrons at isolated GaAs–AlGaAs heterojunction

I. V. Kukushkin, A. S. Plaut,(1) K. von Klitzing,(1) K. Ploog,(1)
and D. Heitmann(1)
Institute of Solid State Physics, Academy of Sciences of the USSR

(Submitted 10 January 1990)
Pis'ma Zh. Eksp. Teor. Fiz. **51**, No. 3, 176–179 (10 February 1990)

The extent of the 1D quantization at an isolated GaAs–AlGaAs heterojunction with quantum filaments has been determined from the recombination-radiation spectra of the recombination of quasi-1D electrons with photoexcited holes. The shape of the potential well varies strongly in a magnetic field and is determined by the number of filled quantum states. An increase in the effective mass of the electrons has been observed in the quasi-1D case.

1. The properties of one-dimensional and zero-dimensional electrons in semiconductor microstructures have recently attracted considerable research interest. These entities have exhibited a quantization of conductivity,[1] a fractional Hall effect,[2] and quantum conductivity fluctuations,[3] among other effects. However, there has not been an adequate study of even the basic characteristics of the energy spectrum of electronic systems of this sort (including the intersubband 1D quantization) or of the shape of the potential well.

In an effort to study the energy spectrum of quasi-1D electrons we have used a spectroscopic method based on a study of the radiative recombination of 2D electrons (and, in the presence of quantum filaments, 1D electrons) with photoexcited holes.[4] This is one of the most powerful methods for studying the electron density of states; in the case of a 2D system, this method permits direct measurements of the intersubband,[5] cyclotron,[6] and spin[7] splittings.

2. In the present study we examined quasi-1D structures made from an isolated GaAs-AlGaAs heterojunction by a holographic method.[8] The quantum filaments in our structures had a width of 150 nm and were separated by a distance of 150 nm. In most of the test samples, only the layer of doped AlGaAs was etched away, down to the spacer (these were the samples of type A), but in some cases we also etched the heterojunction away to a depth of 80 nm (samples of type B). We used isolated heterojunctions with δ doping so that we would be able to study quasi-1D structures by a spectroscopic method.[4] In these structures, a monolayer of acceptor (Be) atoms with a concentration of 10^{10} cm^{-2} was produced at a distance of 20 nm from the interface. By virtue of this monolayer, holes bound to these acceptors were in the immediate vicinity of the electrons during photoexcitation of the sample. It had been shown previously[9] that these heterostructures have several important advantages. First, by varying the power or wavelength of the photoexcitation in them one can vary the electron density in the plane of the heterojunction in a controllable way over a wide range. Second, illumination increases the mobility of the electrons by a factor of

tens from that in darkness. The other experimental details and the parameter values of the structures are given in Refs. 4, 7, and 8.

3. We should first point out that in the absence of a magnetic field the luminescence spectrum of the quasi-1D structures does not exhibit any structural features associated with 1D-quantization subbands, although the resolution of our method was no worse than 1.5 meV (for example, Landau levels were resolved in a magnetic field of 1 T, which corresponds to a cyclotron energy of 1.7 meV). We must therefore conclude that at $H=0$ the intersubband splitting due to the 1D quantization does not exceed 1.5 meV.

Since the energy splitting of the quantum sublevels, ΔE, in the case of a parabolic potential well in a perpendicular magnetic field is determined by both the cyclotron splitting $\hbar\omega_c$ and the 1D splitting $\hbar\omega_0$,

$$(\Delta E)^2 = (\hbar\omega_0)^2 + (\hbar\omega_c)^2, \qquad (1)$$

we would expect an amplification of the splitting of the Landau levels in quasi-1D systems in a magnetic field. By comparing the cyclotron-splitting values measured in the 1D and 2D cases, we can thus determine the magnitude of the 1D quantization, $\hbar\omega_0$.

Figure 1 shows radiative-recombination spectra measured at an isolated GaAs–AlGaAs heterojunction before (2) and after (1) the fabrication of quantum filaments. In most cases we compared different pieces of the same wafer, which were absolutely equivalent until some of them were used to fabricate the quasi-1D structures. It can be

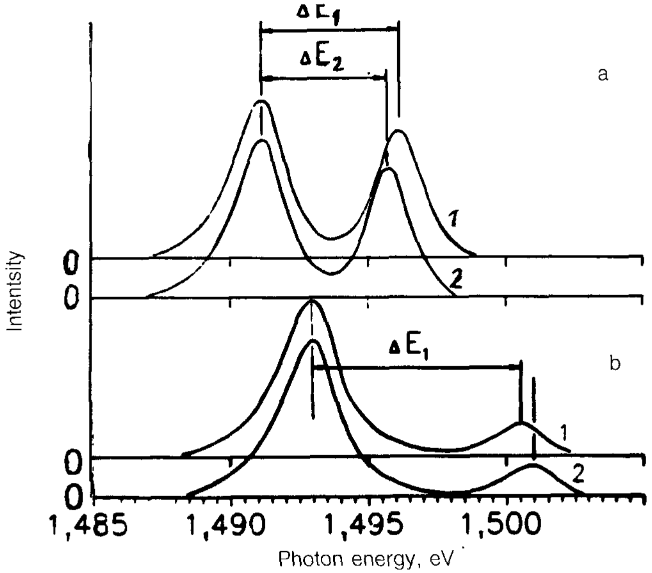

FIG. 1. Radiative-recombination spectra measured for an isolated GaAs-AlGaAs heterojunction. 1—With; 2—without quantum filaments, with $n_S = 2.7\times10^{11}$ cm^{-2}. a) In a magnetic field $H = 3$ T; b) 5T.

seen from Fig. 1 that the presence of quantum filaments does indeed change the splitting of the Landau levels, but these changes do not correspond to expression (1). In the experiments, we observed both an increase and a decrease in the cyclotron splitting in comparison with that in the purely 2D case in the quasi-1D system as we varied the magnetic field. Qualitatively the same behavior of the splitting was observed for all structures and for various electron densities.

Figure 2 shows the splitting of the Landau levels as a function of the magnetic field according to measurements carried out under identical conditions for a quasi-1D structure of type A (with a period $d = 300$ nm) and for a 2D system without quantum filaments with $n_S = 2.7 \times 10^{11}$ cm^{-2} and $\mu = 8 \times 10^5$ cm^2/($V \cdot s$) [the results here are presented in the coordinates corresponding to expression (1)]. It can be seen from the upper part of this figure that in the 2D case we observe a linear dependence $\Delta E(H)$, with a slope determined by the mass of the electrons: $m_e = 0.073 m_0$ at $n_S = 2.7 \times 10^{11}$ cm^{-2} (the inset in Fig. 3 shows the change in the mass of the 2D electrons as a function of their density as found by this method). The behavior of the cyclotron splitting measured in the quasi-1D case is shown at the bottom of Fig. 2 and does not correspond to expression (1). It can be seen from Fig. 2 that in the 1D case abrupt changes occur in the Landau splitting in the luminescence spectrum as the magnetic field is increased. These abrupt changes occur at the time at which the given Landau level is emptied; this emptying is accompanied by the disappearance of the corresponding radiative-recombination line. Furthermore, the characteristic slope of the plot of the square of the splitting (ΔE^2) versus the square of the magnetic field according to measurements on structures with quantum filaments differs from the slope determined

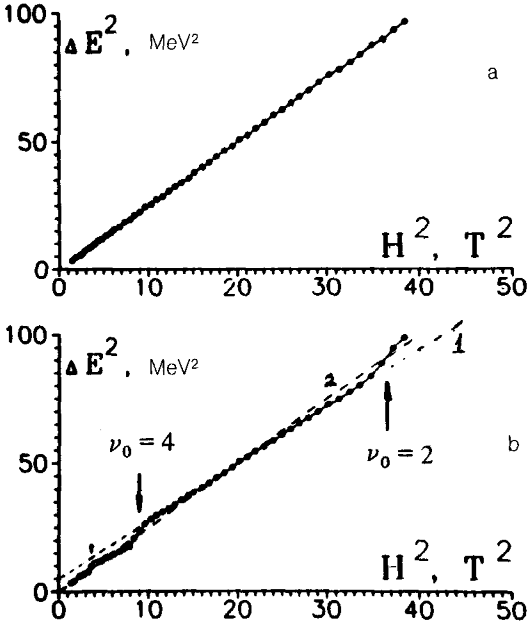

FIG. 2. Splitting of Landau levels versus the magnetic field measured in (a) the 2D case and (b) the 1D case with $n_S = 2.7 \times 10^{11}$ cm^{-2}. The dashed lines show linear least-squares approximations for (2) the 2D case and (1) the 1D case.

in the 2D case. A comparison of the curves of $\Delta E^2(H^2)$ measured in the 1D and 2D cases leads to two conclusions:

a. The effective mass of the electrons in the 1D system is greater than that of the 2D electrons. Specifically, with $n_S = 2.7\times 10^1$ cm^{-2} we have $m_{1D} = 0.077m_0$, and $m_2D = 0.073m_0$ (see the inset in Fig. 3).

b. The shape of the 1D potential well and the magnitude of the size quantization depend on the magnetic field, specifically, on the number of filled Landau levels. The

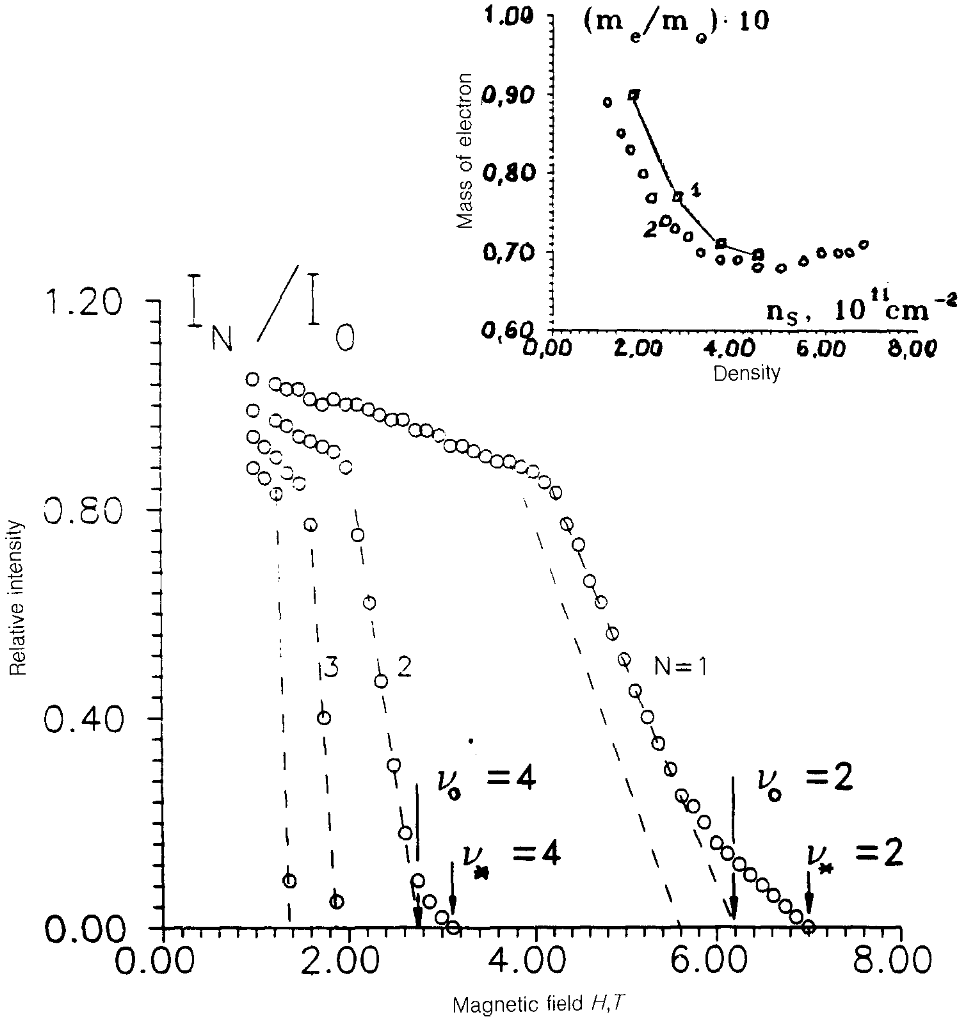

FIG. 3. Relative intensity (I_N/I_0) of the emission line corresponding to the recombination of electrons from the Nth Landau level versus the magnetic field. The inset shows the mass of the 2D and 1D electrons versus the density, as determined from the measured $\Delta E(H)$ curves.

potential well becomes narrower as the magnetic field is strengthened: $\hbar\omega_0 = 1.4$ meV in the case of three filled Landau levels ($N = 3$) and $\hbar\omega_0 = 2.2$ meV at $N = 2$ for a structure of type A with $d = 300$ nm and $n_S = 2.7\times10^{11}$ cm^{-2}.

A change in the width of a potential well should lead to a change in the local 2D density of electrons and thus a change in the filling of the Landau levels. These effects should be manifested as a change in the relative intensities of the corresponding lines in the emission spectrum. Figure 3 shows the relative intensity of luminescence lines corresponding to the recombination of electrons from various Landau levels ($N = 0,1,2,3,4$). The sharp decrease in intensity corresponds to the emptying of a level. It can be seen from Fig. 3 that at small values of N the time at which a Landau level is emptied completely shifts up the magnetic-field scale. This shift corresponds to an increase in the local density n_S. The effect is more pronounced, the stronger H (see the inset in Fig. 3). According to these estimates, the local density n_S increases (and thus the width of the well decreases) by a factor of 1.3 as H is increased from 2 T to 5 T.

We attribute the narrowing of the potential well in a magnetic field observed here to a change in the quantum screening of the potential well by electrons, which occurs as the quantum sublevels are emptied in the magnetic field (a corresponding change in the shape of a well occurs upon a decrease in the number of filled one-dimensional subbands at $H = 0$; Ref. 10).

We wish to thank V. D. Kulakovskiĭ, S. V. Meshkov, V. B. Timofeev, V. I. Fal'ko, and V. B. Shikin for useful discussions.

(1) Max-Planck-Institut for Festkörperforschung, Stuttgart, FRG

---

[1] B. J. Van Wees *et al.*, Phys. Rev. Lett. **60**, 848 (1988).
[2] M. L. Roukes *et al.*, Phys. Rev. Lett. **59**, 3011 (1988).
[3] W. J. Skcopol *et al.*, Phys. Rev. Lett. **56**, 2865 (1986).
[4] I. V. Kukushkin and V. V. Timofeev, Pis'ma Zh. Eksp. Teor. Fiz. **40**, 413 (1984) [JETP Lett. **40**, 1231 (1984)].
[5] I. V. Kukushkin *et al.*, Solid State Commun. **70**, 1015 (1989).
[6] I. V. Kukushkin *et al.*, Phys. Rev. B **37**, 8509 (1988).
[7] I. V. Kukushkin *et al.*, Festkörperprobleme **28**, 21 (1988).
[8] T. Demel *et al.*, Appl. Phys. Lett. **53**, 2176 (1988).
[9] I. V. Kukushkin *et al.*, Phys. Rev. B **40**, 4179 (1989).
[10] S. E. Laux *et al.*, Surf. Sci. **196**, 101 (1988).

Translated by Dave Parsons