Direct determination of the state density of 2*D* electrons in a transverse magnetic field

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(Submitted 13 March 1986)
Pis'ma Zh. Eksp. Teor. Fiz. **43**, No. 8, 387–390 (25 April 1986)

The energy distribution of the state density of 2*D* electrons in a quantizing transverse magnetic field is determined from the radiative-recombination spectra of 2*D* electrons as they recombine with injected holes in Si(100) metal-insulator-semiconductor structures. Oscillations are observed in the width of the Landau levels as a function of the filling factor.

The electron state density in the presence of a random potential of defects is crucial to a discussion of the energy spectrum of two-dimensional (2*D*) systems in a magnetic field. The existing experimental methods generally determine the electron state density at the Fermi level and are based on measurements of the magnetization,[1] the electron specific heat,[2] the magnetocapacitance,[3] the thermally activated conductivity,[4] or the contact potential difference.[5] In none of these methods is the state density determined directly; instead, it is determined by analyzing the results of the measurements with the help of adjustable parameters and under assumptions that require special justification. On the other hand, we know quite well that spectroscopic methods permit the most direct determination of the energy distribution of the density of single-particle states.

The observation of a radiative recombination of 2*D* electrons with photoexcited holes in Si(100) metal-insulator-semiconductor structures has been reported,[6] and the possibilities of this method have been demonstrated. In the case under consideration here, the recombination is indirect, and its probability does not depend on the energy of the recombining particles, while the width of the hole distribution is relatively small, $\leqslant 0.5$ meV. The resulting emission spectrum is a step function, whose width increases linearly with the electron density n_s, unambiguously reflecting the constancy of the state density of 2*D* electrons in a zero magnetic field. Our purpose in the present study was to determine the state density of 2*D* electrons from the radiative-recombination spectra in a transverse magnetic field.

We studied ordinary metal-insulator-semiconductor transistors fabricated on the (100) surface of *p*-type silicon with a boron concentration of 8.3×10^{14} cm^{-3}. The structures have an annular geometry (they are Corbino disks); the thickness of the insulator is 1300 Å; and the maximum mobility of the 2*D* electrons is $\mu = 3$ m^2/(V · s) at $n_s = 4\times10^{11}$ cm^{-2} and $T = 1.6$ K. For the study we use an optical cryostat with a solenoid (*H* up to 8 T). The spectral instrument is a double monochromator with a dispersion of 10 Å/mm in the working region. The emission is observed in the Voigt geometry and is detected under photon-counting conditions with a subsequent buildup of the signal. We wish to stress that all the spectroscopic and magnetotransport measurements were carried simultaneously (Figs. 1 and 2).

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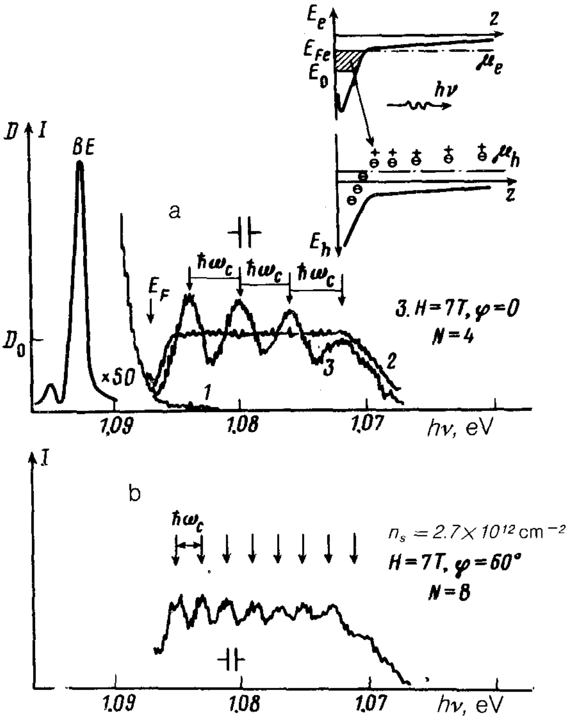

FIG. 1. a: The inset is a band diagram of the recombination of $2D$ electrons with injected holes. The intense line in the emission spectrum (BE), with a peak at $h\nu = 1.0928$ eV, corresponds to a volume emission of excitons bound by boron atoms. Spectrum 1 is the long-wave tail of line BE, magnified by a factor of 50, with $V_g = V_T$ and $n_s = 0$. Curves 2 and 3 show the emission spectra of $2D$ electrons found for $T = 1.6$ K, $n_s = 2.7\times10^{12}$ cm^{-2} and $H = 0$ (spectrum 2) or $H = 7$ T (spectrum 3). The magnitude of the state density in a zero magnetic field, $D_0 = 1.6\times10^{11}$ cm$^{-2}\cdot$meV^{-1}, was found by equating the integrated emission intensities in spectra 2 and 3. b: Emission spectrum found at $T = 1.6$ K, $n_s = 2.7\times10^{12}$ cm^{-2} in an oblique magnetic field $H = 7$ T. The angle between the magnetic field and the normal to the plane of the $2D$ layer is $\varphi = 60°$.

The inset in Fig. 1 is a diagram of the recombination of $2D$ electrons with injected holes bound to boron atoms. We emphasize that there is essentially no depletion layer under conditions of nonequilibrium excitation, and it follows from the magnetotransport measurements that the charge concentration in this layer is $\leqslant 10^9$ cm^{-2}.

Figure 2a shows the conductivity of the $2D$ electrons versus the gate voltage V_g (the threshold voltage is $V_T = 0.24$ V) without a magnetic field and in a strictly transverse magnetic field $H = 7$ T. From these results we can easily determine μ and n_s. We see that with $n_s = 2.7\times10^{12}$ cm^{-2} and $H = 7$ T there are four completely filled Landau levels (each fourfold degenerate in the spin and the valleys; the filling factor is $\nu = 16$). Figure 1a shows the recombination-radiation spectra (TO-phonon component) found for $n_s = 2.7\times10^{12}$ cm^{-2} in the absence (curve 2) of a magnetic field and in the presence (curve 3) of a magnetic field $H = 7$ T. These spectral mea-

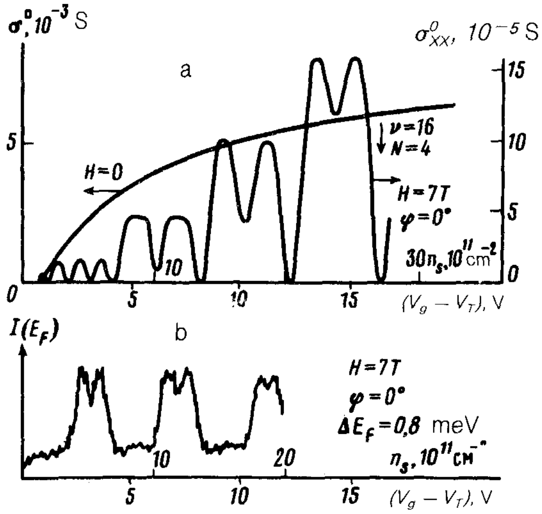

FIG. 2. a: Conductivity (at $H=0$) and magnetoconductivity in a transverse magnetic field $H=7$ T versus the concentration of $2D$ electrons, which is proportional to the gate voltage V_g, reckoned from the threshold voltage V_T. $T=1.6$ K. b: Emission intensity measured at the violet edge of the line, at $H\nu_v=1.0865$ eV, versus the concentration of $2D$ electrons. The transverse magnetic field is $H=7$ T; $T=1.6$ K; the spectral gap is $\Delta E=0.8$ meV.

surements were carried out at the same time as the transport measurements. At $H=0$, the emission spectra reflect the constancy of the state density and have a width equal to the Fermi energy of the $2D$ electrons with $n_s=2.7\times10^{12}$ cm^{-2}. In a transverse magnetic field $H=7$ T and with $n_s=2.7\times10^{12}$ cm^{-2} ($\nu=16$), we clearly see four equidistant lines in the spectrum, corresponding to four Landau levels split by the cyclotron energy $\hbar\omega_c=4$ meV, which corresponds to a cyclotron mass $m_c=0.20\,m_0$. We see that the spin and valley splittings of the levels are not resolved under these conditions. To demonstrate the two-dimensional nature of the electron system under study, we used the method of a rotation of the magnetic field. The angle (φ) of the deviation of the magnetic field from the normal to the $2D$ layer was established and determined from the change in the pattern of Shubnikov-de Haas oscillations. With $\varphi=60°$, $n_s=2.7\times10^{12}$ cm^{-2}, and $H=7$ T, the filling factor exactly doubles, and eight Landau levels turn out to lie under the Fermi surface. Figure 1b shows the spectrum of the recombination radiation found under these conditions. In this spectrum we can clearly see eight Landau levels, whose splitting is half that in Fig. 1a. This is unambiguous proof that the state density of $2D$ electrons is being seen in the recombination spectra.

An important experimental fact is the independence of the spectral position of the violet boundary of the spectrum, corresponding to the Fermi level, from the concentration of $2D$ electrons ($h\nu_v=1.0865\pm0.0005$ eV). Skipping over the detailed reasons for this effect, we simply note that we made use of this circumstance in recording the oscillations of the emission intensity at this spectral position; these oscillations reflect oscillations of the state density at the Fermi level. The results found for $H=7$

T, $T = 1.6$ K, and a spectral gap $\Delta E = 0.8$ meV are shown in Fig. 2b. We see the following:

1) The oscillations in the emission intensity at the Fermi level are periodic in V_g or n_s, demonstrating that the electrons are two-dimensional.

2) The emission of $2D$ electrons in a strong transverse magnetic field is observed only for electrons with spin $S_z = +1/2$ [$2 + 4m < \nu < 4(m+1)$, where $m = 0$, 1,...]. Since the emission in the TO-phonon component of the spectrum is almost completely polarized along the H direction, we must conclude that the recombination of $2D$ electrons involves nonequilibrium holes with $J_z = -3/2$. In this case, optical transitions for electrons with $S_z = -1/2$ are forbidden.

3) The oscillations of the emission intensity and of the conductivity along the V_g scale are strictly correlated with each other.

4) For Landau levels with $N \neq 0$, an intervalley gap is not manifested in the energy spectrum for $\nu = 2m + 1$, but it is seen in the $I(n_s)$ dependence.

To determine the width of the Landau levels, the spin splitting, the valley splitting, and the dependence of these parameters on μ, H, and ν, it is convenient to work with a common lowest level. Noting that the spectroscopic method can furnish answers to these questions, we will discuss only one of them here: the dependence of the width of the Landau level on the filling factor, shown in Fig. 3. We see that the width Γ oscillates as a function of the filling factor, varying by a factor of more than three, reaching a maximum at even values of ν, when the Fermi level is in the middle of the gap (the region of localized states), and reaching a minimum at half-integer values of ν, when the Fermi level lies at the center of the Landau level (the region of mobile states). This ν dependence of Γ can be explained qualitatively in terms of a self-consistent screening of potential fluctuations.[7] A quantitative description of the dependence of Γ, the spin splitting, and the valley splitting on the parameters μ, H, and ν will be published separately.

In summary, the method of recombination radiation of $2D$ electrons during recombination with injected holes provides a direct method for observing the energy distribution of the state density of $2D$ electrons in a transverse quantizing magnetic

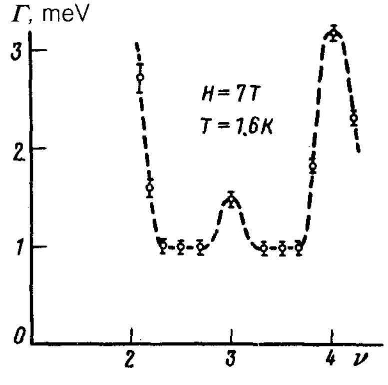

FIG. 3. Width of the lowest Landau level ($N = 0$) versus the filling factor, measured from the recombination spectra for $H = 7$ T and $T = 1.6$ K.

field, and it opens up new opportunities for research. Noteworthy among the problems which can be solved experimentally by this method are that of studying the dependence of Γ on μ, H, and ν; that of studying the spin and valley splittings; and that of determining the magnitude and scale of the potential fluctuations at the $Si\text{-}SiO_2$ interface.

We wish to thank S. V. Iordanskiĭ, É. I. Rashba, and D. E. Khmel'nitskiĭ for useful discussions.

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Translated by Dave Parsons