Enhancement of the skyrmionic excitations due to the suppression of Zeeman energy by optical orientation of nuclear spins

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An effective experimental method for compensation of Zeeman energy of two-dimensional (2D) electrons based on optical pumping of nuclear spins is proposed and used to enhance skyrmionic excitations under conditions of integer and fractional quantum Hall effect. We demonstrate that photoexcitation by circularly polarized light can result in a strong spin orientation of nuclei along (or against) the direction of the external magnetic field and that the energy of the hyperfine contact interaction between 2D electrons and optically oriented nuclear spins can be comparable to the electronic Zeeman energy. It is shown that a compensation of the Zeeman energy by the hyperfine interaction at fixed magnetic field results in an enhancement of skyrmionic excitations and the dependence of the skyrmionic radius as a function of the ratio between Zeeman and Coulomb energies is measured. A strong increase of the skyrmion radius is observed for $E_Z/E_C<0.005$, and the quenching of the skyrmion at $E_Z/E_C=0.011\pm0.001$ is established. Strong electron-nuclear coupling was used for optical detection of the nuclear magnetic resonance from the variation of the polarized luminescence intensity. [S0163-1829(99)12527-X]

INTRODUCTION

It is well known that the spin polarization of the ground state of a two dimensional (2D) electron system in perpendicular magnetic field is defined by a competition between the single-particle Zeeman energy $E_Z=\mu_B gB$ and the many-body energy of Coulomb interaction $E_C=e^2/\epsilon l_B$ (where μ_B-the Bohr radius, g-electronic g factor, B-magnetic field, ϵ- dielectric constant, and l_B-the magnetic length). This was well established both theoretically[1,2] and experimentally[3–5] for the ground states of different fractional Quantum Hall effect (FQHE) states in the extreme quantum limit. The value of the ratio between Zeeman and Coulomb energies E_Z/E_C was especially important for observation of the new collective-charged excitations in 2D-electron system, which are called skyrmions (or spin texture excitations).[6,7] Skyrmionic excitation describes a macroscopically large distortion of the electronic spins in the vicinity of filling factor $\nu=1$. According to theory, the ground state of a 2D-electron system is fully spin polarized at $\nu=1$, however a small deviation from $\nu=1$ results in a strong spin depolarization of the system. The ground state of the system with one additional (to $\nu=1$) spin-reversed electron does not correspond to a single-flipped spin, but involves a smooth rotation of the spin field from antiparallel to a parallel spin, which is spread over a macroscopic size Rl_B. Therefore a characteristic feature of skyrmions is a narrow peak in the filling-factor dependence of the electron-spin polarization in the vicinity of $\nu=1$. The size of the skyrmion R (measured in units of magnetic length) can be determined from the width (or shape) of this peak. Such dependencies were experimentally observed,[8,9] however some controversy[10] exists due to the results obtained by different methods and further investigations are necessary. It follows from theory that the size of this spin-texture excitation (skyrmion) is a strong function of the parameter E_Z/E_C and for zero Zeeman energy its size would be infinitely large.[6] Therefore, to enhance skyrmionic excitations and to unambiguously detect them experimentally one would need to use a method of controllable change of Zeeman energy, which allows to suppress it down to zero.

There are several methods to reduce the Zeeman energy of electrons in GaAs.[11,12] All these methods are based on the influence of the band structure of GaAs on the bare Lande g factor of electrons. The value of the electronic g factor in GaAs is $g=-0.44$ (Ref. 13) and it is defined by the band structure of the material (mainly by the energies of the band gap and of the spin-orbit splitting of the valence band[14]). These energies can be changed by hydrostatic pressure[12] or by quantum confinement.[15] For example, to achieve the limit of $g=0$, one should apply rather strong hydrostatic pressure of about 20 kbars (Ref. 12) or to use very narrow quantum wells with a width of 5.5 nm.[15] However, a modification of the band structure under the pressure results in a strong decrease of the concentration of 2D electrons due to corresponding changes of the band-gap and chemical-potential level. For example, in our samples with highest concentration of 2D electrons measured at zero pressure under illumination ($n_s=6\times10^{11}$ cm^{-2}), the electron density decreases 3 times at $P=10$ kbars and drops to zero at 20 kbars (see also Ref. 16). Such a strong decrease of the electron concentration is accompanied by an even stronger reduction of electron mobility (also several times and more), so that the systems with and without pressure become hardly comparable. Similar problems appear for narrow quantum wells, in which the mobility of 2D electrons is more than one order of mag-

nitude lower, as compared to conventional single heterojunctions. Since a rather weak disorder is enough to destroy Coulomb correlation effects in the 2D-electron system, the gradual reduction of the quality of a sample is not acceptable to study skyrmionic effects, and an alternative method that would allow us to suppress Zeeman energy without changing the electron density and mobility is necessary.

In the present paper, we propose such a method, which is based on compensation of the Zeeman energy by the hyperfine interaction between 2D electrons and the optically-oriented nuclear spins of Ga and As. A high degree of spin orientation of nuclei is achieved by optical pumping with circularly polarized light. We show that under these conditions the hyperfine energy is comparable with the Zeeman energy (both of about 1-2 K in the range of relevant magnetic fields) and therefore an effective compensation, as well as an enhancement, of the Zeeman energy can be obtained. At the same time, we extract the degree of the electron-spin polarization from the degree of circular polarization of the light emitted in the recombination between 2D electrons and photoexcited holes bound to acceptors. Using this technique, we unambiguously demonstrate that a suppression of the Zeeman energy results in a sharp enhancement of the skyrmionic effects, whereas in the opposite case such effects completely disappear. As an *in situ* experimental test, we optically detect nuclear magnetic resonance (NMR), which indicates the importance of the electron-nuclear coupling. Finally, we investigate a detailed dependence of the skyrmion size as a function of the parameter E_Z/E_C.

EXPERIMENTAL TECHNIQUE

In the present paper, we present the results obtained on several low-density $[n_s=(0.36-2.4)\times10^{11}\ \mathrm{cm}^{-2}]$ and high-quality

$$[\text{electron mobility}\ \mu=(0.9-3)\times10^{6}\ \mathrm{cm}^2/\mathrm{Vs}]$$

$GaAs/Al_xGa_{1-x}As$ single heterojunctions with a δ-doped monolayer of Be acceptors ($n_A=2\times10^{9}\ \mathrm{cm}^{-2}$) located in the wide (1 μm) GaAs buffer layer at a distance of 30 nm from the interface.[17] In all samples, a variation of concentration of 2D electrons was performed by use of a top gate. For photoexcitation, we used pulses from a tunable Ti-sapphire (the wavelength was close to 780 nm) laser with a duration of 20 ns, peak power of $10^{-4}-10^{-2}\ \mathrm{W/cm}^2$, and frequency of 10^4-10^6 Hz. Luminescence spectra were detected by a gatable photon counting system with a spectral resolution of 0.03 meV. To analyze circular polarization of the luminescence signal at low temperatures (down to 300 mK), we used a three-fiber optical system with 3 quarter wave plates (for each fiber) located on one linear polarizer in liquid helium near the sample. One fiber was used for measurements of σ^+ and σ^- components of the luminescence and two additional fibers were used for excitation by circularly polarized light (one for left-hand polarization and another for right-hand polarization with respect to direction of light propagation). All three fibers were focused on the same spot of the sample, which was defined by a mask. A change of the direction of the external magnetic field (B), necessary for analysis of circular polarization of luminescence, was accompanied by the corresponding change of input fiber in order to keep the same optical orientation of nuclear spins (parallel or antiparallel) with respect to B. In this case, necessary verification of the power level was performed at $B=0$. Measurements were done in the temperature range of 0.3–1.8 K, and the particular temperature was chosen in accordance with the magnetic-field strength in order to realize a maximal sensitivity of our optical method.[10] For NMR measurements a RF coil was prepared around the sample, which provided the RF magnetic-field-oriented perpendicular to the external magnetic field. Other details of experimental technique will be published elsewhere.

RESULTS AND DISCUSSION

The main idea of the optical pumping method developed by Kastler[18] is that optical excitation results in a selective population in one of the degenerate, or nearly degenerate sublevels coupled through an optical transition. The reason for this is the anisotropy of optical excitation, caused by the transversality of the electromagnetic wave. This anisotropy can be enhanced by using excitation light with linear or circular polarization. For example, in the case of photoexcitation by circularly polarized light, the optical pumping will result in the angular momentum orientation. This is a direct consequence of angular momentum conservation—when polarized photons are absorbed, their momentum is transferred to the medium.

The method of optical pumping is quite universal and for a long time it was used to polarize isolated gas atoms. In solid-state physics, this method was successfully introduced by Lampel.[19] Optical orientation in semiconductors[20] is based on the fact that in the process of the interband absorption of a photon, an electron in the conduction band and a hole in the valence band are generated, which have the total spin equal to the angular momentum of the absorbed photon. Photons with right (σ^+) or left (σ^-) circular polarization have a projection of the angular momentum on the direction of the wave vector equal to $+1$ or -1, respectively. This angular momentum is distributed between the photoexcited electron and hole in accordance with the selection rules, which are determined by the band structure of the semiconductor. In III-V semiconductors (GaAs type) there are several direct interband optical transitions near the center of the Brillouin zone allowed in the dipole approximation. These are: two dipoles rotating clockwise and counterclockwise in the plane perpendicular to the wave vector k (heavy hole band to conduction-band transitions), two dipoles oscillating along the direction of k and two dipoles rotating in the plane perpendicular to k (light-hole band to conduction-band transitions). It is important that transition-matrix elements defining the intensities of the corresponding transitions are different for the optical processes involving heavy holes and light holes. This result coincides with the results obtained by considering the selection rules for optical transitions between two atomic levels with angular momentum $j=\frac{1}{2}$ and $j=\frac{3}{2}$. Similar to the atomic physics selection rules, (σ^+) light is emitted by $|+\frac{3}{2}\rangle\rightarrow|+\frac{1}{2}\rangle$ and by $|+\frac{1}{2}\rangle\rightarrow|-\frac{1}{2}\rangle$ transitions, but the intensity of the first transition is 3 times higher than of the second one. Therefore, in the case of excitation by right-hand polarized light, the ratio of the photoexcited electrons with spins $+\frac{1}{2}$ and $-\frac{1}{2}$ is equal to 3, yielding a degree

of electron spin polarization of 0.5.

Optical pumping of the nuclear spins is a two-step process,[20] which involves in the first step a spin polarization of electrons by circularly polarized light (as described above) and in the second step the electron-spin polarization is transferred to the nuclear-spin system via the contact hyperfine interaction, orienting the nuclear spins parallel to the optically induced electron-spin polarization. Orientation of the nuclear spins results in a static effective nuclear magnetic field (proportional to the degree of nuclear orientation), which in turn acts back on the electron system, changing the Zeeman splitting in the electron spectrum (Overhauser shift). It is important that the energy of the hyperfine interaction, which is usually very small [published maximal value is about 1-2 K (Refs. 20 and 21)], may be comparable to a typical electronic Zeeman energy in GaAs (at $B=5$ T $E_Z=1.5$ K). This fact gives an opportunity to control and manipulate the electron spin-splitting energy at a constant external magnetic field and we use this method both to enhance and to suppress the Zeeman energy.

It has been shown in our previous work[10] that, for the $\nu=2/3$ FQHE state, an increase of the magnetic-field results in a rather sharp transition from a spin-unpolarized state into a spin-aligned ground state. The reason for this effect is a phase transition between two FQHE ground states with different spin configurations, which is very sensitive to the ratio between Zeeman and Coulomb energies. We have studied such spin transitions for all families of FQHE states and these results will be published separately,[22] however, in the present paper we use such transitions to measure the internal nuclear magnetic field, which appears under optical pumping by circularly polarized light. In Fig. 1(a), we show the magnetic-field dependence of the electron-spin polarization (γ_e) measured for 6 different samples (with additional variation of electron density by top gate) at fixed filling factor $\nu=2/3$. To measure the electron-spin polarization, we used the method proposed earlier,[10] which is based on the analysis of the degree of circular polarization (γ_L) of time-resolved radiative recombination of 2D electrons with photoexcited holes bound to acceptors. There are two independent reasons for the resulting circular polarization of the corresponding luminescence. One reason is the spin polarization of the hole system due to the Zeeman effect, which depends on the magnetic field and the temperature of the photoexcited holes (i.e., the population of different Zeeman sublevels). The other reason is the spin polarization of the 2D electrons, which depends on filling factor, temperature, and magnetic field. Fortunately, it is possible to derive the contribution of the holes to the polarization of the luminescence separately by investigating the emission from fully occupied Landau levels (at $\nu=2,4,6\ldots$ and also well below the Fermi surface), because in this case the electron system is spin-unpolarized and it does not influence the polarization of the radiative recombination.[10] It has been demonstrated that the spin polarization of the hole system is defined only by the ratio B/T. This statement makes the foundation of the proposed experimental technique and it is valid only for time-resolved measurements in which a complete relaxation of the photoexcited holes down to the base temperature is provided. Note that the energy relaxation time of the photoexcited holes is rather short at high temperatures (about 2 ns at $T=4$ K), but

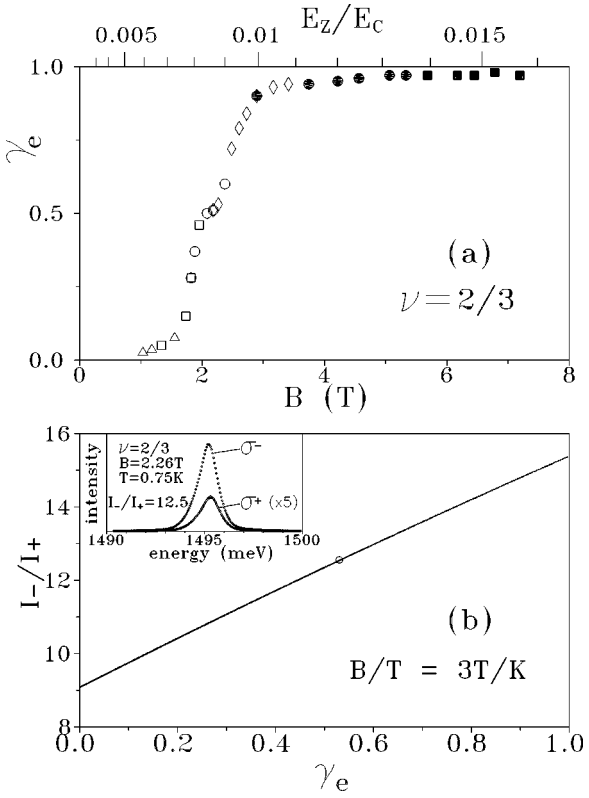

FIG. 1. (a) Magnetic field dependence of the spin polarization of 2D-electron system at the $\nu=\frac{2}{3}$ FQHE state, measured from the analysis of the degree of circular polarization of time-resolved radiative recombination of 2D electrons with photoexcited holes bound to acceptors. The presented data were obtained from 6 different samples (corresponding data are shown by different symbols) and additional variation of the electron concentration was achieved by use of front gate. For photoexcitation linearly polarized light of very low peak power (0.1 mW/cm^2) was used. The variation of the parameter E_Z/E_C with magnetic field is also shown. (b) Calibration dependence (Ref. 10) of the ratio I_-/I_+ on electron spin polarization γ_e, obtained for $B/T=3$ (I_- and I_+ are integrated intensities of luminescence, measured in σ^- and σ^+ polarizations, respectively). From the experimental value $I_-/I_+=12.5\pm0.1$ (shown on the figure), the value of $\gamma_e=0.52\pm0.02$ was derived. Typical time-resolved (delay time 300 ns) luminescence spectra measured in σ^- and σ^+ polarizations for $\nu=\frac{2}{3}$, $B=2.26$ T, $T=0.75$ K are shown in the inset.

at low temperatures the relaxation time strongly increases, and at $T=0.3$ K it is close to 100 ns, so that rather long-time delays (300 ns) were necessary.[10] Therefore, the degree of polarization of the holes can be easily excluded from the polarization of luminescence, which yields in a direct correspondence between γ_L and γ_e for a fixed value of B/T. As a result, our procedure for the experimental determination of the degree of electron-spin polarization is the following: we measure the degree of circular polarization of the luminescence at a fixed magnetic field and a fixed temperature and then we use the calibration dependence obtained in Ref. 10 to determine the value of γ_e. The same procedure was repeated for several other temperatures in order to optimize the procedure. Note that for enhancement of the sensitivity of our method, the temperature value was varied so that $2<B/T<5$ (B and T are measured in Tesla and Kelvin, respectively).[10]

Typical time-resolved (with a delay of 300 ns) luminescence spectra, recorded in σ^- and σ^+ polarizations, and the calibration curve, reflecting a direct correspondence between the degree of circular polarization of the luminescence γ_L and the electron-spin polarization, are shown in Fig. 1(b). It is clear from this figure that for a fixed value of B/T there is a well defined interval of variation of γ_L, which is defined by the spin polarization of the holes. For $B/T=3$ this window corresponds to the interval of the ratios I_-/I_+ between 9.1 and 15.3 [I_- and I_+ are integral intensities of luminescence, measured in σ^- and σ^+ polarizations, respectively, and $\gamma_L=(I_--I_+)/(I_-+I_+)$]. Within this interval, the ratio I_-/I_+ is almost a linear function of γ_e. For $B/T=4$ the low and high limits of I_-/I_+ are: 18.0 and 26.5. After determining the ratio I_-/I_+, we used the calibration curves obtained for different values of B/T and determined γ_e for a fixed magnetic field and various temperatures. It was established that γ_e slightly increases with decreasing temperature, but saturates at low temperatures. This low temperature limit of γ_e is taken as the correct value. It follows from Fig. 1(b) that the ratio I_-/I_+ is very sensitive to γ_e and for 1 percent accuracy of determination of I_-/I_+ realized in our experiment, it allows the measurement of γ_e with an uncertainty of about 0.02 (for $B/T=4$ the uncertainty increases up to 0.03). Other details of this method were published in (Ref. 10), but it is necessary to emphasize that we specially investigated the influence of the nuclear-spin orientation on the spin splitting of the neutral acceptor's levels and that no observable hyperfine coupling of the hole and nuclear spins was detected. This is a rather natural result due to the p type of the Bloch function in the Γ point of the valence band,[20] which gives us an opportunity to derive the electron-spin polarization from the degree of circular polarization of the luminescence[10] without modification of this method.

Figure 1(a) shows the magnetic-field dependence of the electron-spin polarization measured under a low-excitation intensity (peak power density was less than 10^{-3} W/cm^2). For this power level, we did not find any difference for both circularly and linearly polarized light being used for excitation. However, an increase of the power level results in a dramatic change in the electron-spin polarization for the $\nu=2/3$ FQHE state, depending on the polarization of light used for excitation. In Fig. 2, we plot the power-density dependence of the spin polarization of 2D electrons, measured for the $\nu=2/3$ FQHE state in different magnetic fields and under various photoexcitation conditions. Circles correspond to excitation by circularly polarized light, whereas squares correspond to excitation by linearly polarized light. One can see from this figure, that in contrast to the case of excitation by linearly polarized light, which was almost ineffective in changing the electron-spin polarization, the application of circularly polarized light strongly influences the spin configuration of the 2D-electron system. We attribute this effect to the optical orientation of the nuclear spins by circularly polarized light. This understanding is supported by the fact that the left- and right-hand circularly polarized light produce opposite effects, as they orient nuclear spins in different ways—parallel (open circles in Fig. 2) and antiparallel (filled circles in Fig. 2) to the external magnetic field. An effective internal nuclear field is then added or subtracted from the external magnetic field, giving rise to an enhancement or

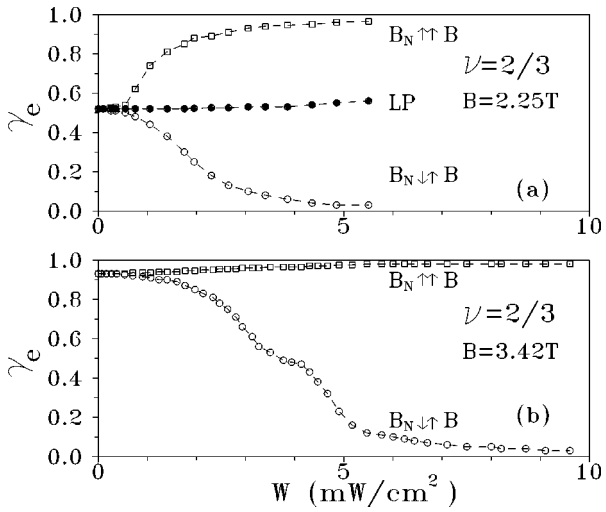

FIG. 2. Power density dependence of the degree of electron-spin polarization measured for the $\nu=\frac{2}{3}$ FQHE state in different external magnetic fields [(a) and (b)] from the degree of polarization of luminescence under different conditions of photoexcitations. Open circles (squares) correspond to photoexcitation by circularly polarized light, which orients nuclear spins against (along) the direction of the external magnetic field and filled circles correspond to excitation by linearly polarized light.

suppression of the effective Zeeman energy, which results in a strong variation of the electron-spin polarization. Note that in our system we have two types of electrons—these are the 2D electrons, which exist without illumination (due to the doping of $Al_xGa_{1-x}As$ layer) and are located very close to the interface (typical width is about of 10 nm), and electrons that are created in the GaAs buffer layer by absorption of photons within a length of about 1 μm (the penetration length of light) and have rather small life time (1 ns) with respect to the recombination with free photoexcited holes. The optical pumping process (both electronic and nuclear) is only due to the spin orientation of the photoexcited electrons, whereas the studied luminescence is due to the 2D electrons. The process of nuclear-spin orientation by photoexcitation is a rather slow process and requires considerable time (a few seconds) to reach a saturation of the nuclear polarization. However, after being polarized, the nuclear-spin system acts on the spins of 2D electrons, changing the degree of polarization of the corresponding luminescence. The observed increase of variation of γ_e with excitation power is due to an increase of the degree of nuclear polarization, which is defined by the intensity of photoexcitation. As for the results obtained for linearly polarized light, it is clear from Fig. 2 that its efficiency for nuclear polarization is very low and gives rise to a small increase of Zeeman energy (in agreement with previous investigations[20]).

To estimate the internal nuclear-magnetic field (B_N) created under the optical pumping conditions, we studied the influence of optical pumping on the threshold dependence, shown in Fig. 1(a), which is sensitive to the Zeeman energy. We analyzed such dependencies measured for the $\nu=\frac{2}{3}$ FQHE state (and also for other incompressible fractions, such as $\nu=\frac{3}{5}$) under optical pumping conditions and found that, for all samples studied, there is a systematic shift in the dependence $\gamma_e(B)$, which is shown in Fig. 3 for different

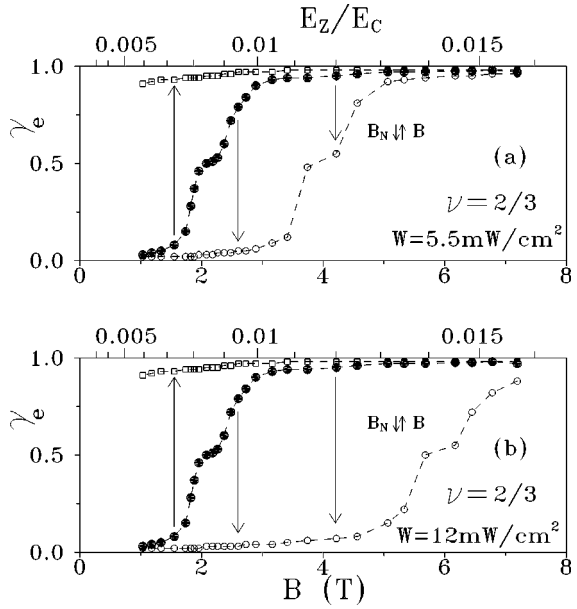

FIG. 3. The influence of optical pumping on the threshold dependence γ_e(B), (similar to the one shown on Fig. 1), measured for the $\nu=\frac{2}{3}$ FQHE state under different excitation powers. The variation of electron-spin polarization obtained under optical orientation of nuclear spins against (along) external magnetic field is shown by open circles (squares).

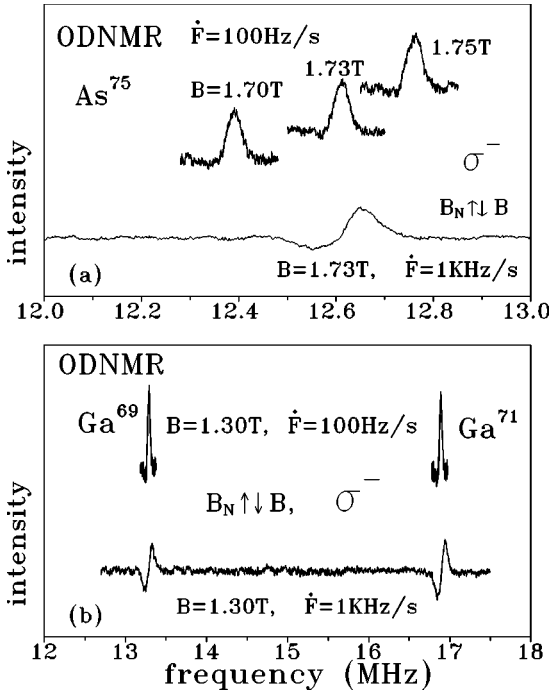

FIG. 4. Nuclear magnetic resonance [As^{75}(a) and Ga^{69}, Ga^{71} (b)], optically detected as a variation of the luminescence intensity (detection in σ^- polarization) as a function of RF frequency, measured in different magnetic fields and for different sweep rates (dF/dt) of RF field under optical pumping, which oriented nuclear spins against the external magnetic field.

excitation powers. It is clear from this figure, that optical orientation of nuclear spins against the external magnetic field results in a shift of the threshold to higher magnetic fields, whereas nuclear spin orientation along the magnetic field shifts the dependence to lower fields. The amplitude of this shift is a measure of the internal nuclear-magnetic field, and illustrates that it could be as high as 1–3 T under strong pumping conditions. However, to determine the exact value of B_N we took into account the change of Coulomb energy as a function of magnetic field and determined an effective Zeeman energy from the value of the electron spin polarization and calibration dependence [shown in Fig. 1(a) for $\nu=\frac{2}{3}$]. Note that this internal nuclear-magnetic field B_N acts only on spins of electrons, but not on their orbital motion. As a check of the procedure we have measured the values of B_N using the calibration curves obtained for different fractional states and found that the values of B_N derived from all fractions were in agreement with each other.

An explanation of the observed shifts in the dependencies of $\gamma_e(B)$ under optical pumping conditions by the electron-nuclear interaction requires a more direct experimental verification of the importance of the coupling between 2D electrons and nuclei. In order to obtain a direct confirmation of such coupling we developed method of optical detection of nuclear magnetic resonance (NMR), which is based on analysis of the time-resolved radiative recombination of 2D electrons with photoexcited holes bound to acceptors. The advantage of this method, in comparison with conventional NMR detection scheme, is that it is selective for nuclei located in the vicinity of the 2D channel. A depolarization of nuclear spins under conditions of the NMR saturation, destroys the internal nuclear field and results in the variation of the electron-spin polarization. As a consequence, the intensity of radiative recombination of 2D electrons with photoexcited holes measured in a dominating circular polarization will also vary in accordance with a change of electron-spin polarization. In Figs. 4(a) and 4(b) we show the optically detected NMR, which was measured for different nuclei and isotopes (As^{75}, Ga^{69}, and Ga^{71}) in various magnetic fields and sweep rates of the RF field. It is clear from these figures that in order to record a correct NMR curve, it was necessary to use rather slow sweep rates dF/dt, which indicates rather long relaxation times in the nuclear system. Optically detected NMR is not only a direct evidence of a strong electron-nuclear coupling, but also an illustration of a remarkable property of the optical-spin orientation method, which gives the possibility to monitor both the electron- and the nuclear-spin polarization. We were able also to measure the Knight shift using the above mentioned possibility to change under different optical pumping conditions (orienting nuclear spins along or against the external magnetic field), from the completely polarized to the unpolarized spin state for $\nu=\frac{2}{3}$. This shift is a change of the nuclear-spin-splitting energy due to electron-nuclear coupling and the variation of electron-spin polarization. The value of the Knight shift, measured at $B=4.2T$ for $\nu=\frac{2}{3}$ from our optically detected NMR was about 17 KHz, which is in reasonable agreement with the data reported in Ref. 8. In addition, NMR was also detected in our samples for luminescence lines corresponding to donor-acceptor recombination in the GaAs buffer layer, which is an indication of a strong nuclear polarization not only at the interface, but also in a rather thick (1 μm) layer of bulk GaAs.

In Fig. 5, we plot the dependence of the internal nuclear-magnetic field on the excitation power. The data were ob-

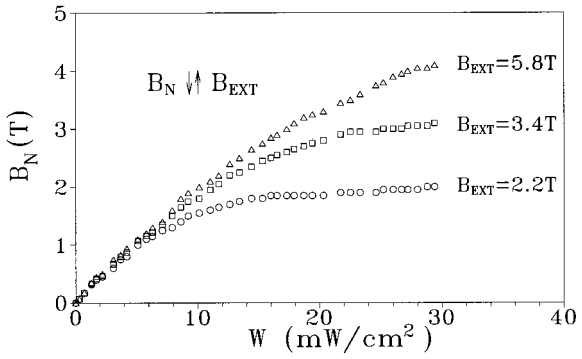

FIG. 5. Power dependence of the internal nuclear-magnetic field B_N, appearing due to optical pumping by circular light, measured in one of the gated samples in different external magnetic fields.

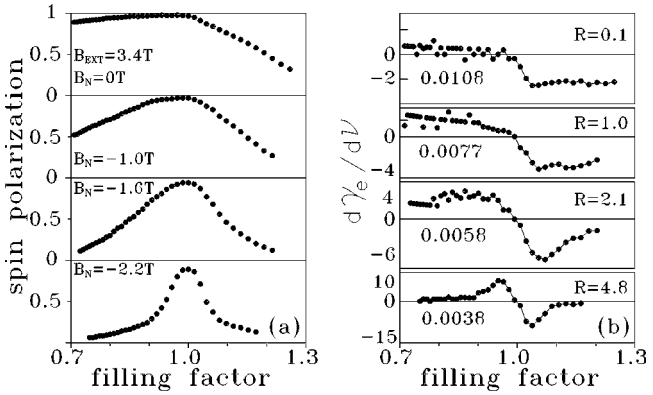

FIG. 6. The dependence of the degree of electron-spin polarization γ_e (a) and its derivative $d\gamma_e/d\nu$ (b) on filling factor, measured for a sample with electron concentration 8.2×10^{10} cm^{-2} under different conditions of optical pumping, which resulted in various internal nuclear fields: $B_N=0$, -1.0, -1.6, and -2.2 T. Negative values of B_N correspond to nuclear-spin orientation against external magnetic field. The size of the skyrmion R was directly measured from the amplitude of discontinuity of $d\gamma_e/d\nu$ for different values of the ratio E_Z/E_C (indicated on right figure): $R=0.1\pm0.3$ for $E_Z/E_C=0.0108$; $R=1.0\pm0.3$ for $E_Z/E_C=0.0077$; $R=2.1\pm0.3$ for $E_Z/E_C=0.0058$; $R=4.8\pm0.3$ for $E_Z/E_C=0.0038$.

tained for the same gated sample at different fixed external magnetic fields under the condition of optical pumping, which orients nuclear spins against B_{EXT}. To measure this dependence at fixed B_{EXT} we changed the concentration of 2D electrons in order to obtain different fractional states at this magnetic field, and, finally, used the corresponding calibration curves for determination of the nuclear field. The results obtained for different FQHE states were in a good agreement with each other. As shown in Fig. 5, by using strong optical pumping, we were able to achieve a high level of nuclear-spin orientation that creates an internal nuclear-magnetic field as high as 4 T. Interestingly, we have observed a saturation of the nuclear field as a function of optical power and it was not possible to get B_N higher than B_{EXT}. A possibility to obtain experimentally such a strong B_N is usually provided by the localization of photoexcited electrons on donor impurities, since the nuclear orientation will take place mainly around these donor impurities (within their Bohr radius). In our case, a similar enhancement most probably appears due to the confinement of photoexcited electrons in the potential well near the interface (an electric field in a buffer layer attracts photoexcited electrons to the interface, increasing their local concentration and therefore nuclear orientation efficiency). Additional localization of photoexcited electrons in the plane may arise due to an attractive (for excitons) potential of the neutral acceptor located in the δ layer near the interface. The binding energy of the exciton to a neutral acceptor is about 2 meV and the corresponding Bohr radius is about 30 nm. Therefore, in our case the internal nuclear-magnetic field can be rather nonuniform, reaching such high values only in the vicinity of acceptor centers. However, since our method is based on locally probing the 2D electrons exactly around these acceptor centers, it allows polarization measurements with compensation of the Zeeman energy by hyperfine interaction.

The possibility to suppress Zeeman energy by the optical orientation of nuclear spins against the external magnetic field was used to enhance skyrmionic effects in the vicinity of $\nu=1$. Figure 6(a) shows the filling-factor dependence of the electron-spin polarization, measured for the same sample around $\nu=1$ ($B_{EXT}=3.4$ T) under different conditions of optical pumping. In this figure we present data obtained both without ($B_N=0$) and with rather strong nuclear optical orientation ($B_N=-1.0$, -1.6, and -2.2 T), with nuclear spins being aligned against B_{EXT}. It is obvious from the figure that an increase of the strength of the nuclear-field results in a decrease of electron-spin polarization in the vicinity of $\nu=1$, and a very narrow peak of spin polarization at $\nu=1$ was observed at the highest negative B_N. This peak is a characteristic feature of the skyrmion, which gives an opportunity to quantify the parameters of these topological textures. In the theory,[7] the size of a skyrmion, R (measured in units of magnetic length) can be measured directly from the filling-factor dependence of the electron spin polarization, $\gamma_e(\nu)$. According to Ref. 7, for $\nu<1$ $d\gamma_e/d\nu=2R$, whereas for $\nu>1$, $d\gamma_e/d\nu=-2(R+1)$. Figure 6(b) shows also the filling-factor dependence of $d\gamma_e/d\nu$, from which we determine the size of the skyrmion R (the value of R was obtained from the amplitude of discontinuity of $d\gamma_e/d\nu$ at $\nu=1$) and its variation under suppression of Zeeman energy (the corresponding values of the parameter E_Z/E_C are indicated on the right figure). Note that values of R derived from the $\nu>1$ and $\nu<1$ regions are close to each other, which illustrates a self-consistency of the obtained results. It is also necessary to mention that the small values of R (like $R=0.15$) obtained in such a procedure most probably indicate that no skyrmion is formed (since smooth rotation of spins in skyrmion requires rather large R), however, in order to compare results measured in different experimental conditions, we apply the same formal procedure and derive the corresponding values of R.

Finally, we have used the described method to measure the basic dependence of the skyrmion size R as a function the parameter E_Z/E_C, which was varied by optical orientation of the nuclear spins. In Fig. 7, we plot this dependence $R(E_Z/E_C)$, measured for different samples from the amplitude of discontinuity of $d\gamma_e/d\nu$ around $\nu=1$. It is clear from this figure, that the size of a skyrmion rapidly grows as the Zeeman energy vanishes and, in contrast, the skyrmion quenches if the parameter E_Z/E_C reaches a value close to 0.011 ± 0.001. These observations are in a contradiction with

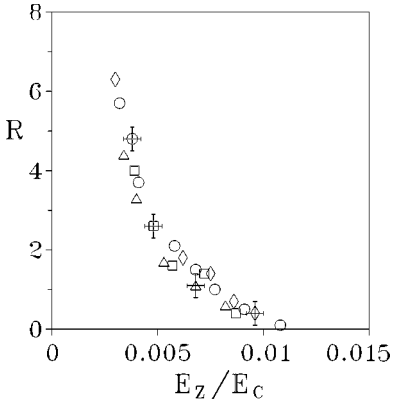

FIG. 7. The dependence of the skyrmion size R (in units of magnetic length) on the ratio between Zeeman and Coulomb energies E_Z/E_C, measured for different samples (shown by different symbols) under variation of the Zeeman energy by optical orientation of the nuclear spins. Typical error bars are indicated.

some previous results,[8,9] which were obtained for the $g=-0.44$ case (in these publications values of $R=2-3$ were measured for $E_Z/E_C=0.015-0.018$), but they are in rather good quantitative agreement with the results obtained for vanishing g factor[11] (skyrmionic effects in this work were significant only for $E_Z/E_C<0.004$). A possible explanation of the apparent discrepancy between our data and the results reported in Refs. 8 and 9 could be due to uncontrollable optically induced nuclear-spin polarization, which also compensated Zeeman energy and resulted in the enhancement of the skyrmionic excitation or due to heating effects.[10]

SUMMARY

In summary, we have developed an effective experimental method for compensation of the Zeeman energy of 2D electrons based on optical pumping of nuclear spins, which was used to enhance skyrmionic excitations. We have demonstrated that photoexcitation by circularly polarized light can result in a strong spin orientation of nuclei both along and against the direction of the external magnetic field and that the energy of the hyperfine interaction between 2D electrons and optically oriented nuclear spins is close to the electronic Zeeman energy. A compensation of Zeeman energy by hyperfine interaction at fixed magnetic field results in an effective enhancement of the skyrmionic excitations around $\nu=1$ and the dependence of the skyrmionic radius as a function of the ratio between Zeeman and Coulomb energies was measured. We demonstrated that the skyrmion quenches in size at $E_Z/E_C=0.011\pm0.001$. A method of optical detection of NMR is suggested and realized, which is based on the analysis of the circular polarization of time-resolved radiative recombination of 2D electrons with photoexcited holes bound to acceptors.

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[1] B.I. Halperin, Helv. Phys. Acta **56**, 75 (1983).
[2] T. Chakraborty and F.C. Zhang, Phys. Rev. B **29**, 7032 (1984).
[3] J.P. Eisenstein, H.L. Stormer, L. Pfeiffer, and K.W. West, Phys. Rev. Lett. **62**, 1540 (1989).
[4] R.G. Clark, S.R. Haynes, A.M. Suckling, J.R. Mallett, P.A. Wright, J.J. Harris, and C.T. Foxon, Phys. Rev. Lett. **62**, 1536 (1989).
[5] L.W. Engel, S.W. Hwang, T. Sajato, D.C. Tsui, and M. Shayegan, Phys. Rev. B **45**, 3418 (1992).
[6] S.L. Sondhi, A. Karlhede, S.A. Kivelson, and E.H. Rezayi, Phys. Rev. B **47**, 16 419 (1993).
[7] H.A. Fertig, L. Brey, R. Cote, and A.H. MacDonald, Phys. Rev. B **50**, 11 018 (1994); **55**, 10 671 (1997).
[8] S.E. Barrett, G. Dabbagh, L.N. Pfeiffer, and K.W. West, Phys. Rev. Lett. **74**, 5112 (1995).
[9] E.H. Aifer, B.B. Goldberg, and B.A. Broido, Phys. Rev. Lett. **76**, 680 (1996).
[10] I.V. Kukushkin, K. von Klitzing, and K. Eberl, Phys. Rev. B **55**, 10 607 (1997).
[11] D.K. Maude, M. Potemskii, J.C. Portal, M. Henini, L. Eaves, G. Hill, and M.A. Pate, Phys. Rev. Lett. **77**, 4604 (1996).
[12] S. Holmes, D.K. Maude, M.L. Williams, J.J. Harris, J.C. Portal, K.W. Barnham, and C.T. Foxon, Semicond. Sci. Technol. **9**, 1549 (1994).
[13] C. Weisbuch and C. Hermann, Phys. Rev. B **15**, 816 (1977).
[14] C. Hermann and C. Weisbuch, Phys. Rev. B **15**, 823 (1977).
[15] M.J. Snelling, G.P. Flinn, A.S. Plaut, R.T. Harley, A.C. Tropper, R. Eccleston, and C.C. Phillips, Phys. Rev. B **44**, 11 345 (1991).
[16] S. Ernst, A.R. Goni, K. Syassen, and K. Eberl, Phys. Rev. Lett. **72**, 4029 (1994).
[17] I.V. Kukushkin, K. von Klitzing, K. Ploog, and V.B. Timofeev, Phys. Rev. B **40**, 7788 (1989).
[18] A. Kastler, Science **158**, 214 (1967).
[19] G. Lampel, Phys. Rev. Lett. **20**, 491 (1968).
[20] F. Meier and B. Zakharchenya, *Optical Orientation* (North-Holland, Amsterdam, 1984).
[21] S.W. Brown, T.A. Kennedy, D. Gammon, and E.S. Snow, Phys. Rev. B **54**, R17 339 (1996).
[22] I.V. Kukushkin, K. von Klitzing, and K. Eberl, Phys. Rev. Lett. **82**, 3665 (1999).