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Polarization-dependent spectral redshifts at $\nu=1$ and $\nu=2$ in a GaAs quantum well in high magnetic fields up to 60 T

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Polarized magnetophotoluminescence measurements performed on a wide parabolic GaAs/Al$_{0.2}$Ga$_{0.8}$As quantum well reveal the presence of spectral redshifts in the energy at filling factors $\nu=1$ and 2. The magnitude of these redshifts depends on the polarization and filling factor. While the values for the case of the σ^- polarization agree with existing theories, the results for the σ^+ polarizations are less understood.

One of the anomalies[1–11] revealed in the magnetophotoluminescence (MPL) experiments performed on the two-dimensional electron gas formed in semiconductor heterostructures [single heterojunctions and single quantum wells (QW's)] was the presence in the spectra of some redshift discontinuities[4,7,10,11] at the filling factors $\nu=1$ and 2. The theoretical model proposed for the case of the σ^- polarization[2,4] shows that the magnitude of the redshift discontinuity in the energy that appears when the magnetic field sweeps through these filling factors will be proportional to the difference between the Hartree-Fock energy (E_{HF}) of the hole formed in the conduction band (CB) after the recombination and the binding energy of the exciton formed before the recombination (E_{EX}), and it will scale as ($\sqrt{B}$) with magnetic field.[4] At $\nu=1$ the value of the discontinuity was shown to be $2\sqrt{2}$ times larger than the value for $\nu=2$. These predictions were confirmed in several recent experiments.[4,9,11]

On the other hand, Osborne *et al.*,[7] as a result of the MPL measurements on a 300-Å QW, found that the value of the redshift at $\nu=1$ is about 1 meV smaller in σ^+ polarization than in the σ^- polarization. Following the theoretical model proposed by Cooper and Chklovskii[3] these authors considered that in the limit of low electronic Zeeman energy (i.e. low magnetic field), the fundamental state of the system will be either an excitonic state (in which a spin-down electron from the conduction band is bound to a hole from the valence band) or a nonexcitonic state in which the valence hole binds to an electronic spin texture, leading to the formation of an excitonic skyrmion. The formation of an excitonic or nonexcitonic initial state is dictated by the separation between the electrons and holes. The different values obtained for the redshifts at $\nu=1$ in the two polarizations were accounted for in the frame of this model by the effects of the valence-band (VB) mixing, which produces a larger binding energy of the exciton in σ^+ polarization than in the σ^- polarization.

In this paper we present the results of the right (RCP) and left (LCP) circularly polarized photoluminescence experiments performed on a wide (1480 Å) GaAs/Al$_{0.2}$Ga$_{0.8}$As parabolic QW with a high carrier density ($(7.6\pm1)\times10^{11}$ cm^{-2} under illumination). The values for the redshifts that we have obtained depend upon the filling factor ($\nu=1$ or 2) and also upon the polarization. In the case of σ^- (LCP) polarization we obtain a rather good agreement with the existing theories,[1–4] and the ratio of the redshifts at $\nu=1$ and 2, $\Delta E^{\sigma-}_{\nu=1}/\Delta E^{\sigma-}_{\nu=2}\approx4$, is close to the predicted value of $2\sqrt{2}$.

The situation is different for the case of the σ^+ (RCP) polarization when, at both $\nu=1$ and 2, the magnitude of the redshift is smaller than the one observed in σ^- polarization. The difference between the redshifts in the energy for the σ^+ and σ^- spectra at $\nu=2$ (1 meV) is almost ten times larger than that at $\nu=1$ (0.1 meV). The ratio of the redshifts in the σ^+ polarization at these two filling factors is $\Delta E^{\sigma+}_{\nu=1}/\Delta E^{\sigma+}_{\nu=2}\approx12.8$, a value which is almost three times higher than the one obtained in the previous case.

The sample used in the measurements was a modulation-doped single wide parabolic GaAs/Al$_{0.2}$Ga$_{0.8}$As QW with a well width of 1480 Å. The MPL studies were performed at a temperature of $T=1.5$ K and the magnetic field was varied from 0 to 60 T using a quasicontinuous long-pulse magnet. The sample was illuminated with a 632.8 nm CW He-Ne laser with a total power of about 1 mW. The carrier concentration under illumination [estimated to be $(7.6\pm1)\times10^{11}$ cm^{-2}] was obtained from low-field Shubnikov de–Hass-type PL intensity measurements. Details of the experiment are described elsewhere.[12]

To describe the optically active recombinations we use the following conventions[13] adopted in the literature: For band-to-band absorption or emission, σ^+ light couples only the $-3/2$ heavy-hole (HH) state and the $-1/2$ electron state, whereas σ^- couples only $+3/2$ HH state with $+1/2$ electron state. For excitons, σ^+ couples to the exciton made up of $+3/2$ HH state and $-1/2$ electron state, whereas σ^- couples to the exciton made up of $-3/2$ HH and $+1/2$ electron. In Fig. 1 and Fig. 2 we show the recorded spectra around filling factor $\nu=1$ ($B=31.4$ T, Fig. 1) and $\nu=2$ ($B=15.7$ T, Fig. 2). The σ^+ polarization involves recombinations of the $-1/2$ spin electrons from the lowest Landau level whereas the σ^- polarization involves recombinations of the $+1/2$ spin electrons from the lowest Landau level. The evolution of the energy with magnetic field displays a redshift discontinuity at filling factors in the range of $0.85\leqslant\nu$

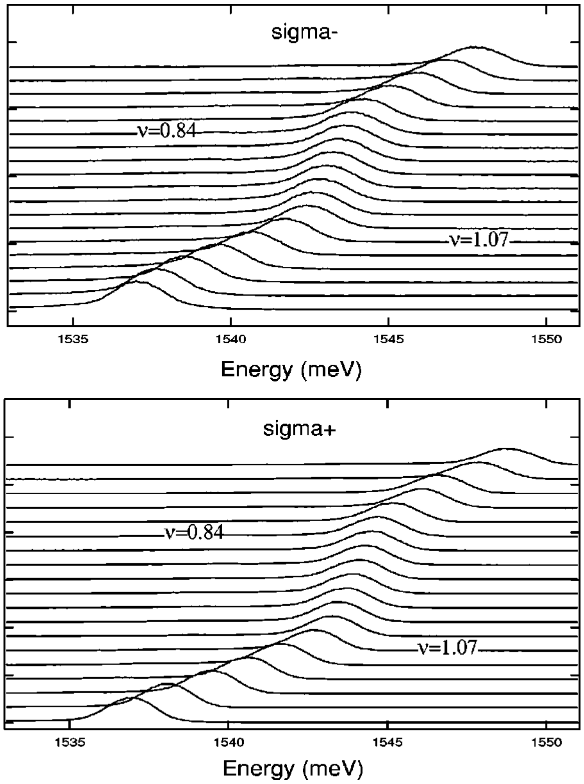

FIG. 1. The MPL spectra recorded in σ^+ and σ^- polarizations around filling factor $\nu=1$ ($B\approx 31.4$ T) show the presence of redshifts in the energies. The values are $\Delta E^{\sigma^-}_{\nu=1}\approx 6.5$ meV and $\Delta E^{\sigma^+}_{\nu=1}\approx 6.4$ meV, respectively.

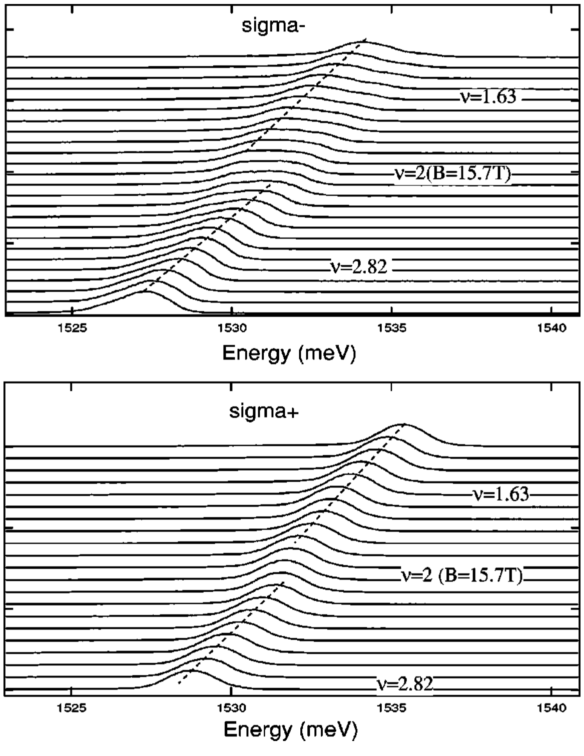

FIG. 2. The MPL spectra recorded in σ^+ and σ^- polarizations around filling factor $\nu=2$ ($B\approx 15.7$ T) show the presence of the redshifts in the energies. The values are $\Delta E^{\sigma^-}_{\nu=2}\approx 1.6$ meV and $\Delta E^{\sigma^+}_{\nu=2}\approx 0.6$ meV, respectively.

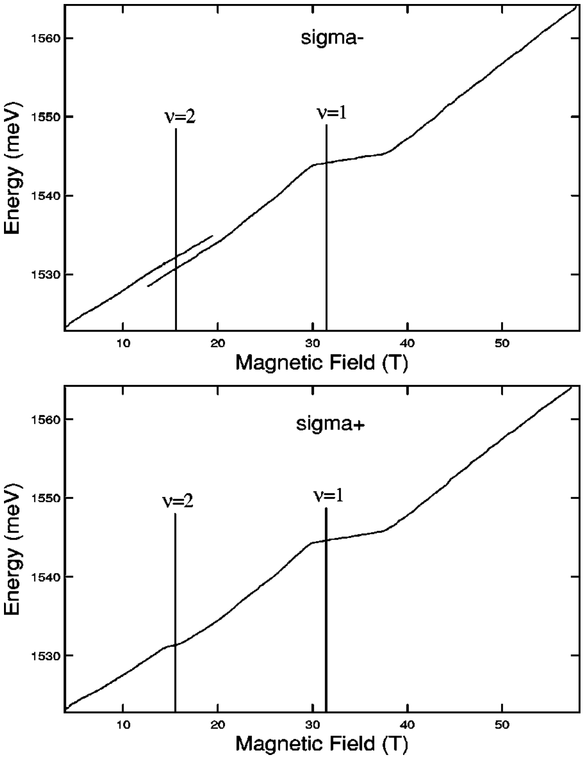

FIG. 3. The evolution of the energy with magnetic field in the σ^+ and σ^- polarizations. The position of the filling factors $\nu=1$ and 2 was determined within a limit of 15% error such that $B_{\nu=1}=31.4\pm 4$ T and $B_{\nu=2}=15.7\pm 2$ T.

$\leqslant 1.07$. The values of these redshifts are almost the same in both spectra: 6.5 meV in σ^- polarization and 6.4 meV in σ^+ polarization. At $\nu=2$ ($B=15.7$ T) the redshifts are much smaller than those found at $\nu=1$ as seen in Fig. 3. However, the magnitude of the redshift at $\nu=2$ is much *larger* for the σ^- polarization ($\Delta E^{\sigma^-}_{\nu=2}\approx 1.6$ meV) than for the σ^+ polarization ($\Delta E^{\sigma^+}_{\nu=2}\approx 0.6$ meV).

The redshifts in the energy have been explained theoretically[2,4] for the case of the σ^- polarization by taking into account the different initial and final states in the electron configuration for filling factors slightly larger or smaller than 1 or 2. In Fig. 4 we show the initial and final states for the σ^+ and σ^- polarizations at $\nu=1$. Following Gravier *et al.*,[4] we find that for σ^- polarization at filling factors ν slightly smaller than 1 ($\nu=1^-$), the final state contains a hole on the $+1/2$ electron level. This will lower the recombination energy by an amount $E_{HF}=\sqrt{(\pi/2)}e^2/\epsilon l$, the Hartree-Fock energy due to the interaction between the hole in the CB and holes in the VB. On the other hand, for filling factors ν slightly larger than 1 ($\nu=1^+$) the initial-state energy, and consequently the recombination energy, will be lowered from the band-gap energy by an amount B_{EX}, the binding energy involving a $-1/2$ spin electron. After the recombination, a spin wave with zero total angular momentum will remain, and therefore the Zeeman energy of the final state will equal the Zeeman energy of the initial state. The net result will be a redshift in the energy with increasing field given by

$$\Delta E^{\sigma^-}_{\nu=1}=E_{HF}-B_{EX}. \tag{1}$$

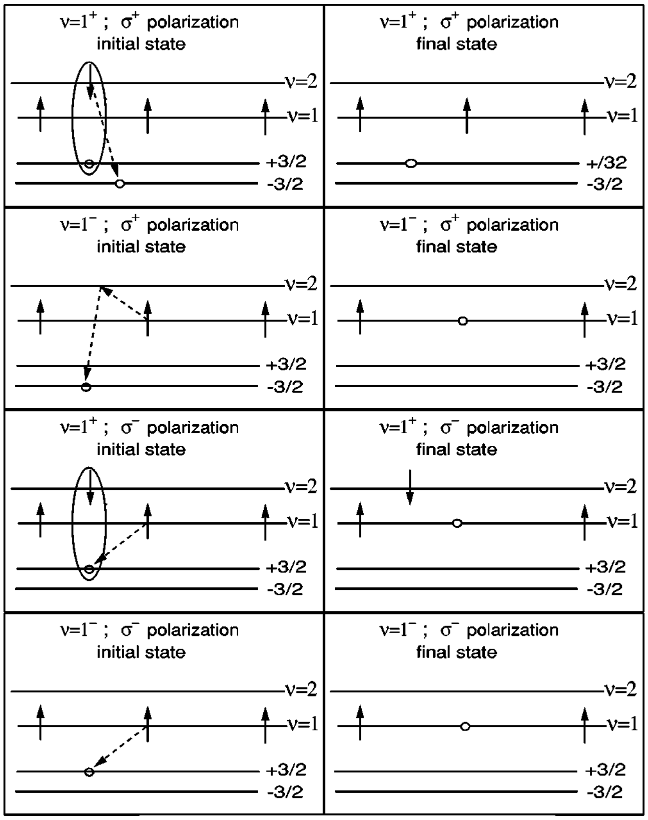

FIG. 4. The initial and final states in the σ^+ and σ^- polarizations around $\nu=1$.

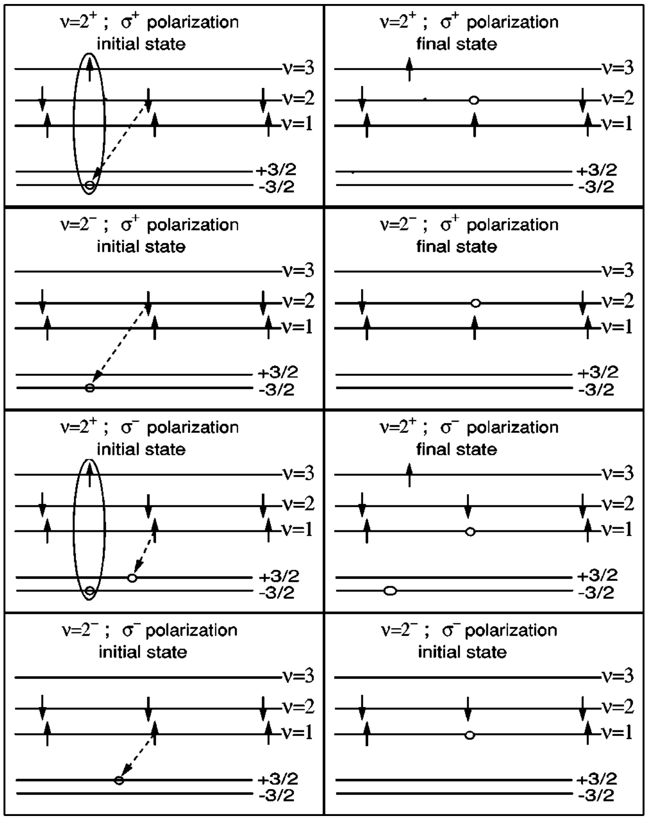

FIG. 5. The initial and final states in the σ^+ and σ^- polarizations around $\nu=2$.

The measured value of the redshift for our sample is $\Delta E^{\sigma-}_{\nu=1}=6.5$ meV.

For recombinations around the filling factor $\nu=2$, the results are shown in Fig. 5. In the case of σ^- polarization, Hawrylak and Potemski[2] showed that the value of the redshift should be

$$\Delta E^{\sigma-}_{\nu=2}=(E_{HF}-B_{EX})/2. \tag{2}$$

If we include in this formula the fact that the magnetic field coresponding to $\nu=2$ is half the value of the magnetic field for $\nu=1$, we obtain a value of the redshift at $\nu=2$ which must be $2\sqrt{2}$ times smaller than the value of the redshift at $\nu=1$. Equation (2) takes into account the formation in the final state of an inter-Landau-level excitation with the total angular momentum 1, as well as the fact that the initial state at filling factors $\nu=2^+$ will show the presence of excitons formed with an electron from the Landau level $n=1$. The experimental value that we have obtained $\Delta E^{\sigma-}_{\nu=2}=1.6$ meV is in good agreement with this prediction.

For the case of the σ^+ polarization, which involves recombinations of electrons from the $-1/2$ spin level with holes from the $-3/2$ spin level, the values of the redshifts which we measured at both $\nu=1$ and $\nu=2$ are different from those obtained in the σ^- polarization.

Firstly, we notice that the change in excitonic binding energy due to the VB mixing cannot account for the smaller values of the redshifts measured at $\nu=1$ and 2 in the RCP spectra. In the framework of the discussed model,[2,4] the initial exciton formed at $\nu=1$ will always involve a spin-down electron while the one formed at $\nu=2$ will involve a spin-up electron regardless of the polarization. For this reason, the value of the binding energy of the excitonic state formed before recombination (B_{EX}) will be the same in both σ^+ and σ^- spectra. Also, Andreani and Pasquarello[14] calculated the effect of the VB coupling on the exciton binding energies in GaAs/Al$_x$Ga$_{1-x}$As QW's with different widths. Their results show that in the case of a 200 Å QW, the difference in the binding energies for the σ^+ and σ^- excitons is about 1 meV, a value ten times larger than the difference of the redshifts obtained at $\nu=1$, but comparable with the value we have obtained for $\nu=2$.

One important observation for the case of the σ^+ polarization around $\nu=1^-$ is that the initial state does not have any $-1/2$ spin electrons available. In order to observe a σ^+ polarized signal it is necessary to have an electron with a spin $-1/2$ which can occur as a result of a spin-flip[7,15] process. This will generate an increase in the energy of the initial state (E_S) as a result of the perturbations induced in the now incomplete $+1/2$ electronic level such that the recombination energy will be lowered by an amount $E_{HF}-E_S$ from the band-gap recombination energy. The net result is that the redshift of the energy at $\nu=1$ in the σ^+ polarization will now given by

$$\Delta E^{\sigma+}_{\nu=1}=E_{HF}-B_{EX}-E_S. \tag{3}$$

We believe that the small perturbation energy (E_S) of the $+1/2$ electronic level after the electron spin-flip could be at the origin of the smaller redshift in the energy observed in σ^+ polarization around $\nu=1$.

The smaller redshift in the energy at $\nu=2$ in the σ^+ polarized spectra compared with the σ^- spectra may be due to the effects of the VB mixing. It has been shown[16] that the VB Landau levels have a strong nonlinear dependence with magnetic field as a result of VB mixing and that the effects are stronger for the case of the $-3/2$ VB energy level than for the $+3/2$ energy level. The degree of band mixing increases with magnetic field and as a result the binding energy of the $e\uparrow h\downarrow$ exciton is larger than that of the $e\downarrow h\uparrow$ exciton. For recombination processes around $\nu=2^+$ in the σ^+ spectra, the initial state is excitonic, involving a $+1/2$ electron from the $n=1$ Landau level and a $-3/2$ hole in the VB hole. The recombination, as indicated in Fig. 5, will take place between this hole and a $-1/2$ spin electron from the $n=0$ Landau level. We suggest that, due to the increased binding energy of the initial exciton, a second electron will be captured by the excitonic complex shortly before the recombination, leading to the formation of a negatively charged magnetoexciton (X^-). Equation (2) would then be modified such that

$$\Delta E_{\nu=2}^{\sigma+}=(E_{HF}-B_{X^-})/2, \tag{4}$$

where B_{X^-} is the binding energy of the X^- state. From our data we estimate its binding energy to be about 2 meV larger than that of the initial neutral exciton.

In conclusion, magnetophotoluminescence measurements performed on a high-density modulation-doped wide parabolic quantum well displayed, at the filling factors $\nu=2$ and 1, the presence of an energy redshift with increasing magnetic field whose magnitude was different for σ^+ and σ^- polarizations. While in the case of σ^- polarization the value for the redshifts can be accounted for in the framework of the existing theories, the data for the σ^+ polarization requires a much more detailed analysis of the interparticle correlations.

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[1] B.A. Muzykantskii, Zh. Éksp. Teor. Fiz. **101**, 1084 (1992) [Sov. Phys. JETP **74**, 897 (1992)].

[2] P. Hawrylak and M. Potemski, Phys. Rev. B **56**, 12 386 (1997).

[3] N.R. Cooper and D.B. Chklovskii, Phys. Rev. B **55**, 2436 (1997).

[4] L. Gravier, M. Potemski, P. Hawrylak, and B. Etienne, Phys. Rev. Lett. **80**, 3344 (1998).

[5] F. Plentz, D. Heiman, L.N. Pfeiffer, and K.W. West, Phys. Rev. B **57**, 1370 (1998).

[6] B.B. Goldberg *et al.*, Surf. Sci. **263**, 9 (1992); P. Vincente *et al.*, Solid State Commun. **96**, 901 (1995); G. Finkelstein, H. Shtrikman, and I. Bar-Joseph, Phys. Rev. B **56**, 10 326 (1997).

[7] J.L. Osborne, A.J. Shields, M.Y. Simmons, N.R. Cooper, D.A. Ritchie, and M. Pepper, Phys. Rev. B **58**, R4227 (1998); Physica B **249-251**, 538 (1998).

[8] R.J. Nicholas, D. Kinder, A.N. Priest, C.C. Chang, H.H. Cheng, J.J. Harris, and C.T. Foxon, Physica B **249-251**, 553 (1998).

[9] M.J. Manfra, B.B. Goldberg, L. Pfeiffer, and K. West, Phys. Rev. B **57**, R9467 (1998).

[10] B.B. Goldberg, D. Heiman, M. Dahl, A. Pinczuk, L. Pfeiffer, and K. West, Phys. Rev. B **44**, 4006 (1991).

[11] S. Takeyama, G. Karczewski, T. Wojtowicz, J. Kossut, H. Kunimatsu, K. Uchida, and N. Miura, Phys. Rev. B **59**, 7327 (1999).

[12] C.H. Perry, Y. Kim, and D.G. Rickel, Physica B **246-247**, 182 (1998).

[13] T.C. Damen, K. Leo, J. Shah, and J.E. Cunningham, Appl. Phys. Lett. **58**, 1902 (1991); M. Potemski, J.C. Maan, A. Fasolino, K. Ploog, and G. Weimann, Surf. Sci. **229**, 151 (1990).

[14] L.C. Andreani and A. Pasquarello, Europhys. Lett. **6**, 259 (1988).

[15] H.V. van Kestern, E.C. Cosman, F.J.A.M. Greidanus, P. Dawson, K.J. Moore, and C.T. Foxon, Phys. Rev. Lett. **61**, 129 (1988).

[16] M. Altarelli, in *Heterojunctions and Semiconductor Superlattices*: Proceedings of the Winter School, Les Houches, France, edited by G. Allan *et al.* (Springer-Verlag, Berlin, 1986), pp. 12–37.