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Nonreciprocal magneto-optical effects in quantum wells

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In this paper we predicted and observed a new magneto-optical effect - the “effect of parity". The effect is manifest as a redistribution of the oscillator strengths between spatially even and odd center of mass quantized states of the exciton in the quantum well.

1 Introduction The main distinguishing feature of the exciton in a semiconductor crystal is that it is not trapped at a specific location, and can move freely through the crystal. The motion of excitons in crystals was first noted in [1]. Despite the fact that the word "exciton" is often used for a localized state, all the basic features of the freely moving exciton are conserved for such conditions.

In our previous work it was discovered that the exciton Zeeman splitting increases when the exciton moves through the crystal [2] and this was investigated in detail. This phenomenon is explained by the mixing of the relative motion of the electron and hole in the exciton and the center of mass exciton motion. As the result of this mixing, the 1s state of the internal motion in the exciton is mixed with all p states that have non-zero orbital angular momentum. This mixing is proportional to the square of the exciton center of mass wave-vector and leads to the growth of the Zeeman splitting. Thus the observed effect was linear in magnetic field and quadratic in the exciton center of mass wave-vector. In this paper we predict a new phenomenon linear in both the wave vector of the exciton and the magnetic field, and present the first experimental evidence for this effect.

2 Theoretical results The exciton center of mass Hamiltonian including terms linear in the magnetic field and the center of mass wavevector can be built by the method of invariants [3]:

$$H_{exc} = H_{ex}(0) + H_{ex}(H) + H_{ex}(K) + H_{ex}(KH) + H(K^2). \tag{1}$$

Here,

$$H_{ex}(0) = E_0 + H_{exch},$$

where H_{exch} is the Hamiltonian of the exchange interaction in the exciton and

$$H_{ex}(H) = g_e \mu_B (\vec{\sigma}\cdot\vec{H}) - 2\mu_B \left[\tilde{k}\left(\vec{J}\cdot\vec{H}\right) + \tilde{q}\left(H_x J_x^3 + H_y J_y^3 + H_z J_z^3\right)\right].$$

is the Hamiltonian (linear in magnetic field) describing the exciton Zeeman splitting.

$$H_{ex}(K) = C[K_x J_x \left(J_y^2 - J_z^2\right) + K_y J_y \left(J_z^2 - J_x^2\right) + K_z J_z \left(J_x^2 - J_y^2\right)]$$

is the Hamiltonian linear in the exciton wavevector.

In a crystal of T_d symmetry the Hamiltonian of the exciton kinetic energy is:

$$H\left(K^2\right)=\frac{\alpha^2}{2m_e}\hbar^2\ K_z^2 I+\frac{\beta^2}{2m_0}\left(\gamma_1+\frac{5}{2}\gamma\right)\hbar^2\ K_z^2 I$$
$$-\frac{\gamma}{m_0}\beta^2\hbar^2\ (K_z J_z)^2\ ,$$

$$\alpha_{hh,lh}=\frac{m_e}{m_e+m_{hh.lh}}\ ,\quad \beta_{hh,lh}=\frac{m_e}{m_e+m_{hh.lh}}\ ,$$

$$m_{hh}=\frac{m_0}{\gamma_1-2\gamma}\ ,\qquad m_{lh}=\frac{m_0}{\gamma_1+2\gamma}\ .$$

The Hamiltonian which is bilinear in wave vector and magnetic field is [4, 5]:

$$\begin{aligned}H_{ex}(KH)=B_1\left[K_x H_x\left(J_y^2-J_z^2\right)+c.p.\right]\\+B_2\left(\left[\vec{H}\vec{K}\right]_x\left\{J_y\cdot J_z\right\}+c.p.\right)\end{aligned}\qquad(2)$$

where $\vec{J}$ is the operator for total angular momentum 3/2; $\vec{\sigma}$ is the spin operator; g_e is the g-factor of the electron; $\tilde{k},\tilde{q}$ are Luttinger parameters for the exciton; H_{exch} is the exchange interaction in the exciton; m_{hh}, m_{lh} are heavy and light hole masses; and $x\,\|\,[100]$, $y\,\|\,[010]$, $z\,\|\,[001]$. We will neglect the exchange interaction in this paper.

In structures of D_{2d} symmetry these Hamiltonians in general are very similar, but the coefficients of (*x*, *y*) and *z* components are different. Here we consider only the Faraday geometry. In this case the term bilinear in *H* and *K* is:

$$BK_zH_z\left(J_x^2-J_y^2\right)$$

Or

$$B\ K_zH_z\times\begin{bmatrix}0&0&\sqrt{3}&0\\0&0&0&\sqrt{3}\\\sqrt{3}&0&0&0\\0&\sqrt{3}&0&0\end{bmatrix}.$$

We can write the following system of equations in linearly polarized components, setting aside the exciton-photon interaction but taking into account the Zeeman effect:

$$\mathcal{E}_{HH}^0(-i\nabla)|x\rangle_{HH}-iB\nabla_zH_z|x\rangle_{LH}+i\mu g_{HH}H_z|y\rangle_{HH}$$
$$\mathcal{E}_{HH}^0(-i\nabla)|y\rangle_{HH}+iB\nabla_zH_z|y\rangle_{LH}-i\mu g_{HH}H_z|x\rangle_{HH}$$
$$\mathcal{E}_{LH}^0(-i\nabla)|y\rangle_{LH}+iB\nabla_zH_z|y\rangle_{HH}-i\mu g_{LH}H_z|x\rangle_{LH}$$
$$\mathcal{E}_{LH}^0(-i\nabla)|x\rangle_{LH}-iB\nabla_zH_z|x\rangle_{HH}-i\mu g_{HH}H_z|y\rangle_{LH}$$

Here $\mathcal{E}_{HH}(-i\nabla)$, $\mathcal{E}_{LH}(-i\nabla)$ are the energies of the exciton ground states for heavy and light holes and $|x\rangle_{HH}$, $|x\rangle_{LH}$ are the *x* components of the wavefunction for heavy and light hole excitons respectively.

For exciton-polaritons in linearly polarized components:

$$\begin{aligned}&(\mathcal{E}_{HH}^0(-i\nabla)-\hbar\omega)|x\rangle_{HH}-iB\nabla_zH_z|x\rangle_{LH}\\&+i\mu g_{HH}H_z|y\rangle_{HH}=d_xE_x\ ,\end{aligned}\qquad(3a)$$

$$\begin{aligned}&(\mathcal{E}_{HH}^0(-i\nabla)-\hbar\omega)|y\rangle_{HH}+iB\nabla_zH_z|y\rangle_{LH}\\&-i\mu g_{HH}H_z|x\rangle_{HH}=d_yE_y\ ,\end{aligned}\qquad(3b)$$

$$\begin{aligned}&(\mathcal{E}_{LH}^0(-i\nabla)-\hbar\omega)|y\rangle_{LH}+iB\nabla_zH_z|y\rangle_{HH}\\&-i\mu g_{LH}H_z|x\rangle_{LH}=\frac{d_y}{3}E_y\ ,\end{aligned}\qquad(3c)$$

$$\begin{aligned}&(\mathcal{E}_{LH}^0(-i\nabla)-\hbar\omega)|x\rangle_{LH}-iB\nabla_zH_z|x\rangle_{HH}\\&-i\mu g_{HH}H_z|y\rangle_{LH}=\frac{d_x}{3}E_x\ .\end{aligned}\qquad(3d)$$

Here d_i is the dipole matrix element of the corresponding exciton transition and E_x is the *x* component of the electric field.

Let consider the spectral range close to the heavy hole exciton resonance. Neglecting magnetic field effects for light-hole excitons in comparison with the heavy hole-light hole splitting and substituting the result into the heavy exciton equations we obtain:

$$\begin{aligned}&(\mathcal{E}_{HH}^0-\hbar\omega)|x\rangle_{HH}+i\mu g_{HH}H_z|y\rangle_{HH}\\&=d_xE_x+BH_z\frac{1}{3}\frac{d_x}{\left|\mathcal{E}_{LH}^0-\mathcal{E}_{HH}^0\right|}i\nabla_zE_x\ ,\end{aligned}\qquad(4a)$$

$$\begin{aligned}&(\mathcal{E}_{HH}^0-\hbar\omega)|y\rangle_{HH}-i\mu g_{HH}H_z|x\rangle_{HH}\\&=d_yE_y-BH_z\frac{1}{3}\frac{d_y}{\left|\mathcal{E}_{LH}^0-\mathcal{E}_{HH}^0\right|}i\nabla_zE_y.\end{aligned}\qquad(4b)$$

We can see that the exciton-light interaction contains not only the electromagnetic field but also its gradient.

In a wide quantum well, the exciton center of mass motion is quantized in the transverse direction (z). The states of the exciton size quantization are determined by the condition $K_zL=\pi N$ where *L* is the quantum well width and *K* is the center of mass wave vector. The wave-functions of these quantized states are odd or even in relation to the reflection at the center of quantum well. In the case that the quantum well width satisfies the condition $KL=\pi 2N$, only spatially even states interact with light, whereas if the quantum well width satisfies the condition $K_zL=\pi(2N+1)$ only the odd states are optically active [6]. This effect emerges due to different overlap of the electromagnetic field and exciton wave-functions.

physica status solidi c

One can see in (4a) and (4b) that the case of a bilinear contribution (2) this selection rule is not valid, and both odd and even states become optically active at any QW width L From the formulae (4a) and (4b) it follows that the redistribution of the oscillator strength can be observed when incident and reflected light are linearly polarized in the directions: (*100*) or *(010)* or *(001)*. Also the effect of the redistribution can be found if the incident light is linearly polarized in the direction *(100)* or *(010)* or *(001)* but circularly polarized light is detected. At the same time the effect should be absent in linearly polarizations along *(110)* or *(011)* or *(101)*. For the case that both incident and detected light are circularly polarized we will see only normal Zeeman splitting.

3 Experimental results All these conclusions are confirmed by experiments. Figure 1 shows the reflectivity spectra of a $GaAs/Al_{0.3}Ga_{0.7}As$ quantum well structure of width 300 nm taken at normal light incidence. We see the states of exciton-polariton size quantization. This spectrum was recorded with linearly polarized incident light and the circularly polarized components of the reflected light in σ^+ and σ^- polarizations were analyzed (σ^+ and σ^- spectra are coinciding in the absence of magnetic fields). Due to the fact that the quantum well thickness is close to λ/2 in this reflectivity spectrum we see only even states.

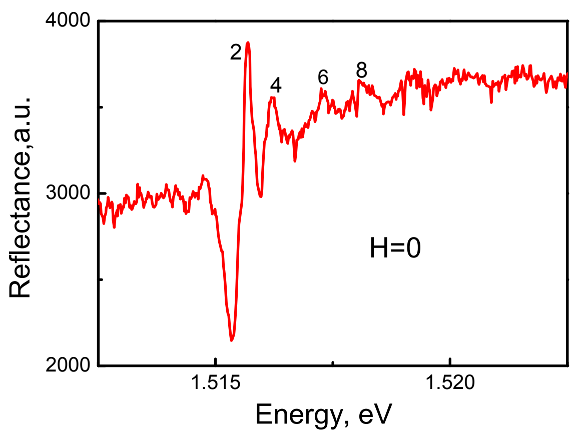

Figure 1 Reflectivity spectra taken from GaAs/AlGaAs QW of 280 nm width. Incident light is linearly polarized along (100) and circular polarization of the reflected light is analyzed. Numbers of the exciton quantized states are shown.

When a magnetic field is applied, in addition to the conventional Zeeman splitting we can find a redistribution of the intensities of lines with different parity. In Fig. 2 we present reflectivity spectra taken from the same structure in magnetic field of 5 T. The incident light was linearly polarized in (100) and the reflected light was analyzed in σ^+ and σ^- polarizations. In this figure we removed Zeeman splitting of exciton lines to emphasize the effect of parity. One can see that in magnetic fields odd states of exciton quantization become observable in addition to even states. All these facts confirmed the theoretical conclusions contained in the formulas (4).

This redistribution of the oscillator strength between even and odd states, according to the formulae (4), is essential for the heavy hole states that are close in energy to the light hole exciton states. When the energy distance between light hole and heavy hole increases this effect disappears. This conclusion is completely confirmed by the spectra of CdTe/CdMgTe quantum wells, in which the heavy–light hole splitting is high due to strain.

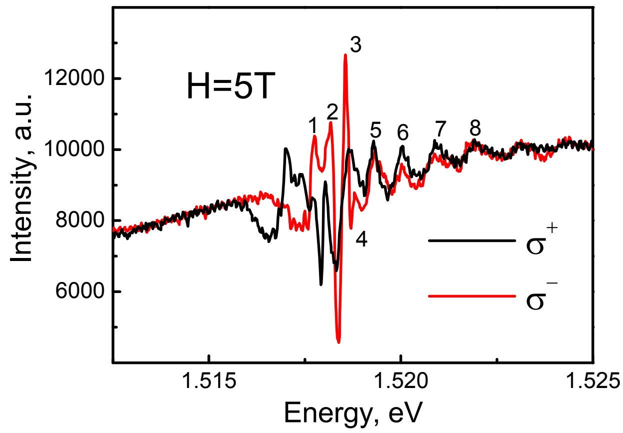

Figure 2 Reflectivity spectra taken from the same structure at magnetic field of 5 Tesla. Incident light is linearly polarized along (100), the circularly polarization is analyzed in σ^+ and σ^- polarizations. Numbers of the exciton quantized states are shown.

Figure 3 shows the reflectivity spectra of the quantum well studied taken in linear polarizations along (110) direction. One can see that there are no effects additional to the conventional Zeeman splitting again according to the formulas (4). Indeed, summarizing the formulas (4a) and (4b) we can see that the contribution from the gradient of electromagnetic field is vanishes for the signal ($|x\rangle \pm |y\rangle$) that corresponds to the polarization along (110).

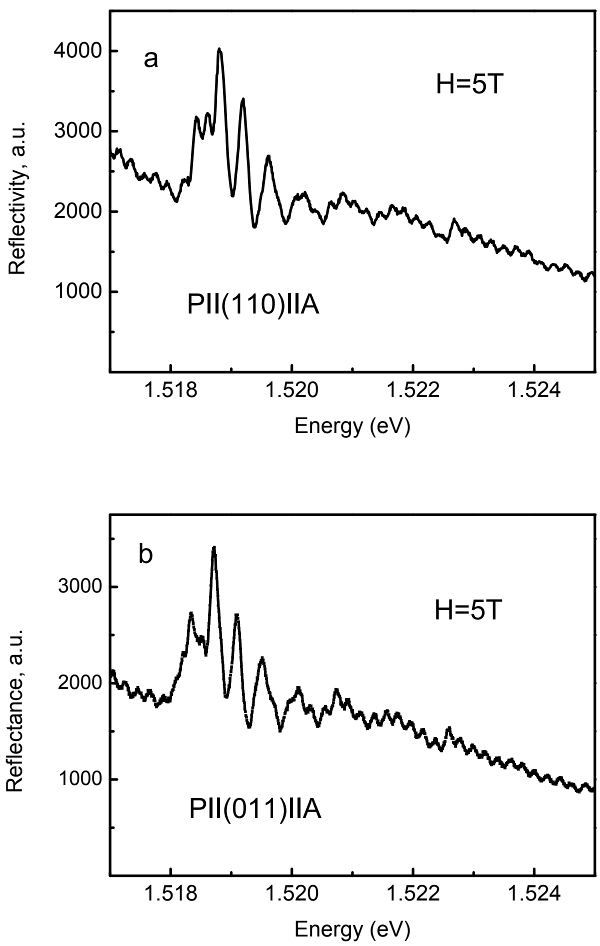

Figure 3 The same spectrum. Incident light is linearly polarized along (110) and the linear polarization is analyzed along (110) – (a); and incident light is linearly polarized along (011) and the linear polarization is analyzed along (110) – (b).

4 Conclusion New magneto-optical effect – «the effect of parity» is predicted and observed in optical spectra of quantum well structures. This effect manifested as redistribution of oscillator strength from odd to even states of exciton center of mass quantization and vice versa from even to odd when magnetic field is applied.

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