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Designing of GaAs/AlGaAs multiple quantum wells to enhance magnetooptical Kerr effect†

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In this article we study magnetooptical Kerr effect (MOKE) of the $GaAs/Al_{0.31}Ga_{0.69}As$ multiple quantum wells (MQWs). Firstly, comparing the measured spectra of MOKE with the theoretical ones we established parameters of the sample such as energy of excitons in quantum wells, their oscillation strengths, damping coefficients. Then using the obtained parameters we tried to establish which quantum well from the 30 quantum wells existing in the sample is the most responsible for the value of rotation of polarization plane of light in measured MOKE. Finally we analysed how the geometry of the structure influences the value of the rotation. We changed the widths of all barriers between the wells of MWQs while the other parameters remained unchanged. It occurred that the rotation of polarization plane changed periodically. A big enhancement of MOKE can be obtained for certain widths of barriers. It confirms that the interference plays a crucial role in the MOKE.

Keywords: magnetooptical Kerr effect (MOKE), GaAs/AlGaAs MQWs, interference.

1. Introduction

It is known that interband magnetooptical spectroscopy is a sensitive method of studying of low-dimensional structures. It allows us to study different properties of electron gas in such structures. For example, MOKE can be used for investigating the states of spin polarization of electron gas [1]. However, we should remember that the measured signal obtained by the spectroscopy depends not only on the properties of the electron gas but also that the geometry of the sample plays a crucial role

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†The measurements have been performed at the International Laboratory of High Magnetic Field and Low Temperatures, Wrocław, Poland.

which was analyzed in various papers [2, 3]. In this article we discuss how to rearrange the existing complex multilayer structure (the Table) containing MQWs to enhance the measured MOKE.

2. Experimental setup and results

As we can see in the Table our real sample, which served as a starting point to our calculations, consists of a thick substrate of GaAs (0.5 mm) on which a buffer layers were deposited (no. 1–54) as well as the main structure of MQWs (no. 55–174). The whole structure is covered with a cap (no. 178). The sample was grown by molecular beam epitaxy (MBE). The width of GaAs quantum wells in the MQWs structure is 183 Å and they are separated by asymmetrically δ-doped $Al_{0.31}Ga_{0.69}As$ barriers of width of 402 Å (= 75 + 327 Å). The barriers are doped with Si atoms (donors) at the distance of 75 Å from one side of the barriers.

The measurements of magnetorotation of the reflected light were performed in the Faraday configuration, at the temperature of 1.8 K. It means that the external magnetic field was parallel to the direction of propagation of linearly polarized monochromatic light which in our case propagated along the growth direction. The polarization state of the light reflected from the sample was analysed by the rotating polarizer placed in front of a detector. The applied two-channel lock-in amplifier allowed us to measure amplitude of the electric signal and its phase shift in relation to the reference signal. It was shown in SUITS'S paper [4] that the phase

T a b l e. Structure of the investigated sample.

Number of the layer	Material	Percentage of Al [%]	Concentration n [cm^{-2}]	Width d [Å]	Loops	Number of repetitions
1	GaAs			4582		1
2	AlAs			975		1
3–51	GaAs			23	start	25
4–52	AlAs			22	end	25
53	AlGaAs	31.2		467		1
54	GaAs			183		1
55–171	AlGaAs	31.2		75	start	30
56–172	Si-δ		4e11	0		30
57–173	AlGaAs	31.2		327		30
58–174	GaAs			183	end	30
175	AlGaAs	31.2		75		1
176	Si-δ		4e11	0		1
177	AlGaAs	31.2		467		1
178 cap	GaAs			183		1

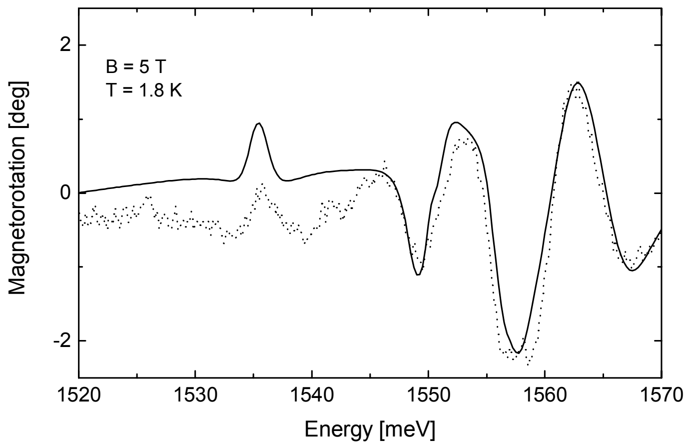

Fig. 1. Juxtaposition of the measured (dot line) and calculated (solid line) MOKE spectra for the sample (see the Table) placed in magnetic field of 5 T and temperature of 1.8 K.

shift of the signal is equal to the doubled value of rotation of polarization plane of the reflected light. In structures consisting of thin layers multiple internal reflections take place which cause the superposition of the Faraday rotation and Kerr rotation so we have to talk about an effective magnetorotation. Sometimes we call it MOKE to stress that the magnetorotation is measured in the reflection configuration.

Figure 1 shows the spectrum of magnetorotation $\Theta(E)$ measured in magnetic field $B = 5$ T and the calculated one which satisfactorily resembles the measured curve. To explain the origin of the lines we calculated the energies of the quantum levels in the MQWs using the local density approximation method. For both the conduction and valence bands we used one particle approximation which is not very accurate for the latter one, but allows us to expect that in all probability the spectral lines correspond to the interband transitions between exciton states of the quantum wells.

3. Theoretical approach

Generally speaking, there are two equivalent ways of theoretical analysis of MOKE caused by multilayer structures. Transfer matrix model [5–7], as well as recurrence formalism [4, 8] take into account multiple reflections between boundaries of each layer. In our simplified approach we assumed that each layer is homogeneous which imposes constancy of the refractive index with a depth in the layer. Moreover, we assumed that the layers had parallel and optically flat interfaces. In this paper to obtain the rotation of polarization plane we calculated the reflection coefficient for the whole multilayer system for the left (r^-) and right (r^+) circular polarizations of light using the recurrence formula. According to this procedure, reflection coefficient

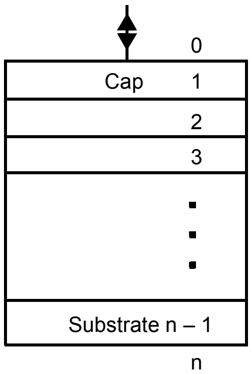

Fig. 2. Configuration of thin layers.

of the structure consisting of n–1 layers placed between mediums 0 and n (see Fig. 2) can be calculated from equation:

$$r^{\pm} = r_{0n}^{\pm} = \frac{r_{0n}^{\pm} + r_{1n}^{\pm}\exp(2i\beta_1^{\pm})}{1 + r_{0n}^{\pm} r_{1n}^{\pm}\exp(2i\beta_1^{\pm})} \tag{1}$$

where

$$r_{1n}^{\pm} = \frac{r_{12}^{\pm} + r_{2n}^{\pm}\exp(2i\beta_2^{\pm})}{1 + r_{12}^{\pm} r_{2n}^{\pm}\exp(2i\beta_2^{\pm})} \tag{2}$$

where

$$r_{2n}^{\pm} = \frac{r_{23}^{\pm} + r_{3n}^{\pm}\exp(2i\beta_3^{\pm})}{1 + r_{23}^{\pm} r_{3n}^{\pm}\exp(2i\beta_3^{\pm})} \tag{3}$$

and so on until:

$$r_{n-2,\,n}^{\pm} = \frac{r_{n-2,\,n-1}^{\pm} + r_{n-1,\,n}^{\pm}\exp(2i\beta_{n-1}^{\pm})}{1 + r_{n-2,\,n-1}^{\pm} r_{n-1,\,n}^{\pm}\exp(2i\beta_{n-1}^{\pm})} \tag{4}$$

where $\beta_i^{\pm} = (\omega/c)d_i\sqrt{\varepsilon_i^{\pm}}$ denotes the dephazing and absorption of the electromagnetic wave after crossing the layer i of thickness d_i described by dielectric function $\varepsilon_i^{\pm}$ for both polarizations of light.

Coefficient of reflectivity for each interface can be obtained from expression:

$$r_{i,\,i+1}^{\pm} = \frac{\sqrt{\varepsilon_i^{\pm}} - \sqrt{\varepsilon_{i+1}^{\pm}}}{\sqrt{\varepsilon_i^{\pm}} + \sqrt{\varepsilon_{i+1}^{\pm}}} \tag{5}$$

Then the rotation of the whole structure was calculated from equation [7]:

$$\Theta = \frac{1}{2}\arg\left\{\frac{r^+}{r^-}\right\} \tag{6}$$

Dielectric functions of the quantum wells (for left and right polarization of light) in which excitonic transitions dominate were described by Lorentzian oscillators:

$$\varepsilon^{\pm}(\hbar\omega) = \varepsilon_1\left(1 + \frac{S^{\pm}}{\hbar\omega_0^{\pm} - \hbar\omega - i\Gamma^{\pm}}\right) \tag{7}$$

with such parameters as the oscillator strengths $S^{\pm}$, damping coefficients $\Gamma^{\pm}$ and transition energies $\hbar\omega_0^{\pm}$ for left and right polarizations; $\hbar\omega_0^{\pm} = \hbar\omega_0 \pm \frac{1}{2}g_{\mathrm{eff}}\mu_B B$ where $\hbar\omega_0$ is the transition energy without magnetic field, g_{eff} – effective g-factor representing total spin splitting of energy levels in valence and conduction bands, μ_B – Bohr magneton and B – magnetic field; ε_1 is a dielectric function which represents the other allowed transitions. Refractive indices of layers were taken from the literature. Refractive index of GaAs was taken from SELL's *et al.* [9] whereas absorption coefficient from STURGE's [10] and SELL's and CASEY [11] papers. Refractive index of AlAs was given by FERN and ONTON [12] and refractive index of $Al_{1-x}Ga_xAs$ was given by CASEY *et al.* [13]. We neglected absorption of AlAs and $Al_{1-x}Ga_xAs$ for the wavelengths we used in our experiment. As in the mentioned papers the real parts of refractive indices were given for the room temperature only, we had to use Blakemore's equation [14] to obtain values appropriate for $T = 1.8$ K.

4. Results and analysis

From our exemplary fitting (Fig. 1) it followed that for the exciton with the transition energy $\hbar\omega_0 = 1550$ meV the oscillator strengths and damping coefficients for both polarizations are $S^{\pm} = 0.15$ meV and $\Gamma^{\pm} = 0.8$ meV, respectively. The effective g-factor is $g_{\mathrm{eff}} = 2.5$. Of course each of the 30 QWs had the same parameters but we do not know if it means that the excitons in the QWs contribute to the whole measured rotation in the same degree. To check it we carried on our calculations in the same way as during the fitting but with one exception. We left the Lorentzian oscillator representing exciton only in one QW, but with the same values of the parameters as previously when there were excitons in all 30 QWs. Figure 3**a** shows the calculated spectra of MOKE for only one exciton line existing in only one out of the 30 QWs. The number above each spectrum informs about in which QW, counting from the side of the cap, the left exciton exists. It is noticeable that the values of the MOKE slightly decrease for spectra coming from QWs placed deeper in the sample. At first sight it is surprising that the values of MOKE for single excitons in only one of the 30 QWs (Fig. 3**a**) are only a bit smaller than the rotation caused by the whole real structure

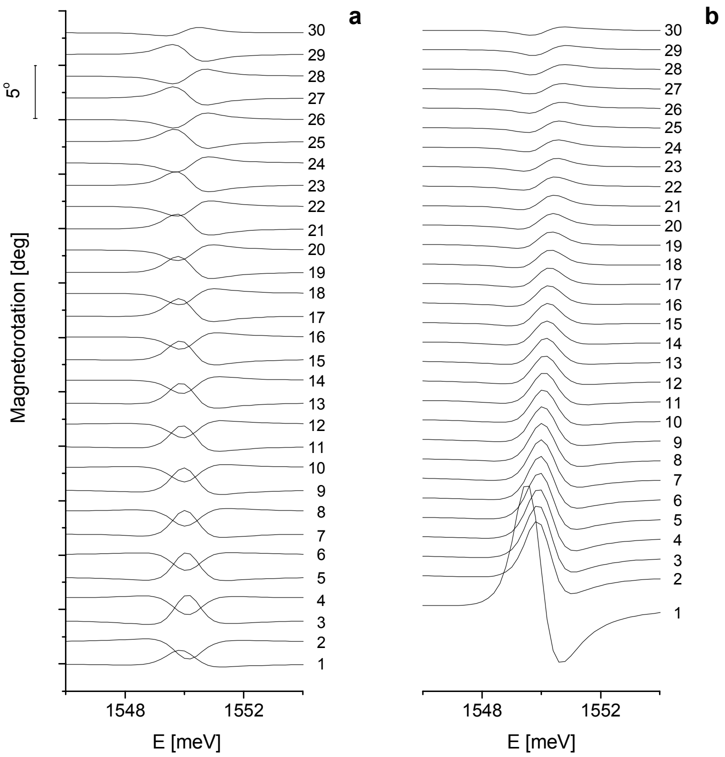

Fig. 3. **a** – Calculated spectra for multilayer structure presented in the Table but for assumption that exciton exists only in one out of 30 QWs. The number above each spectrum informs about in which QW, counting from the side of the cap, the left exciton exists. According to the Tab.1 the width of barriers in the MQWs structure are d_b = 402 Å (= 327 + 75Å)); **b** – as in (**a**) except for the width of barriers which are d_b = 968 Å.

in which excitons exist simultaneously in all QWs (Fig. 1). Before we explain this it is worth noticing that the spectra for odd QWs are similar one to another but are different from those for even QWs which are as if they were in the opposite phase. This explains why the rotation of light does not significantly increase after passing through the whole structure.

The question is how to rearrange the same QWs to obtain much bigger values of MOKE. We tried changing the width of all 30 barriers simultaneously. The result is presented in Fig. 4**a** which shows that the calculated MOKE changes periodically with two periods. One period in our case is equal to about 1170 Å. For appropriately prepared sample, *i.e.*, for low damping coefficient (Fig. 4**b**) or in higher magnetic field (Fig. 4**c**) there are regions of barriers width for which the value of MOKE reaches 90 or –90 degrees. Moreover we can notice that the period remains the same. The smaller damping coefficient can be obtained by ensuring smoother interfaces between layers in a real sample and better repetition of the parameters of the layers of which the whole MQWs structure consists. A detector containing such structure would be extremely

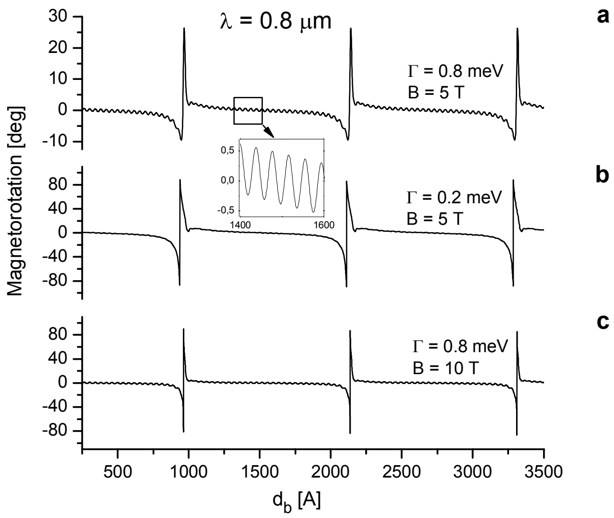

Fig. 4. Calculated dependence of magnetorotation on the thickness of barriers in the structure of MQWs for wavelength $\lambda = 0.8$ μm: **a** – curve obtained for parameters obtained from fitting presented in Fig. 3, **b** – curve obtained for the same parameters as in (**a**) except for damping coefficient which is reduced to $\Gamma = 0.2$ meV, **c** – curve obtained for the same parameters as in (**a**) but for magnetic field $B = 10$ T.

sensitive. For bigger damping coefficients the values of MOKE are suppressed but still for the same barriers MOKE reaches high values (Fig. 4**a**). It occurred from our calculations that the very high values of MOKE are obtained when the optical thickness of the period of QWs is a multiplication of a half of the wavelength of the incident light

$$n_b d_b + n_w d_w = k\frac{\lambda}{2} \tag{8}$$

where: n_b, n_w – refractive indices of barriers and wells, d_b, d_w – widths of barriers and wells, respectively, λ – wavelength of the incident light, k – integer number.

To verify this condition we changed widths of the buffer layers which had no noticeable effect on the period and positions of the very high values of MOKE in Fig. 4.

We also checked that when the condition (8) is fulfilled the spectra of MOKE for exciton in single QWs have similar shape (have the same “phase”) no matter in which one out of the 30 QWs the exciton existed (Fig. 3**b**). So when the light passes through the sample in which every QW has exciton causing similar rotation of polarization plane of light, the total MOKE increases dramatically. We can notice that for our real sample in which the widths of barriers are 402 Å the k factor is $k \cong 0.5$. It explains why every second exciton gives almost the same spectrum of rotation but rotations from neighbouring QWs contribute as if they were in the opposite phase (Fig. 3**a**). For barriers of widths $d_b = 940$ Å, $k = 1$ and that is why the big enhancement of total MOKE takes place. The same situation repeats periodically for $k = 2, 3\ldots$, *i.e.*, in our case for barriers of widths $d_b = 2110$ Å, 3280 Å and so on.

The full width at half maximum (FWHM) for the curves from Fig. 4 is a very important parameter from the technological point of view. The value of the parameter for the curve from Fig. 4**b** is about 30 Å, which is promising for using such calculations to obtain appropriate structures. In this case, for instance, for the first maximum the width of barriers should be $d_b = 940 \pm 15$ Å. This accuracy is within reach of modern nanotechnology.

When we have a closer look at the insertion in Fig. 4**a** we notice that MOKE changes also with another period though this time the changes are only of a few degrees. It occurred that the period corresponds to interference of light on the whole structure of thin layers (1–178) grown on the GaAs substrate. This time for the maximal values of magnetorotation the following condition is fulfilled:

$$\sum n_i d_i = m\frac{\lambda}{2} \tag{9}$$

where the sum goes through all layers and m is an integer number. The condition (9) corresponds to the constructive interference investigated for the whole free standing structure of $GaAs/Al_{0.3}Ga_{0.7}As$ MQWs described in the paper [2]. The values of Kerr effect obtained in that paper are rather small because the conditions of measurements are far from fulfilling the Eq. (8).

Designing the appropriate structure to enhance MOKE is very important for magnetooptical memories which seem to have promising future. If measured MOKE is bigger, the detector becomes more sensitive so we can reduce its dimensions and still have a detector sensitive enough for different applications. In that case the resolution of the memory can be higher and thus its capacitance can be improved.

5. Conclusions

In conclusion, we would like to stress that MOKE caused by multilayer structures similar to the one described in this paper depends not only on properties of excitons in each QW but also on the period of the structure. It means that interference plays a crucial role. The extremely big enhancement of magnetorotation can be achieved when the optical width of period of MQWs is a multiplication of a half of the wavelength of the incident wave.

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