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Dynamical Kerr effect in a quantum-well AlGaAs/GaAs structure under circular optical excitation

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Abstract. Time-resolved magneto-optical Kerr effect is used for studying the ultrafast spin dynamics in a semiconductor heterostructure AlGaAs/GaAs in the subpicosecond time range. Results are analyzed on the basis of the semiconductor Bloch equations.

Introduction

In recent years, there has been a growing interest in the investigation of the spin dynamics down to subpicoseconds in semiconductors and semiconductor heterostructures. In particular, the processes governing the coherence between excited and ground states of photo-carriers are of utmost intrest for ultrafast electronics. Various techniques have been used in the past for the study of spin dynamics, such as photoluminescence or Faraday effect [1, 14, 3]. However, the magnetooptical Kerr effect has been rarely applied for the studies of semiconductors, though it is a standard practice in linear and nonlinear optics of ferromagnets [4]. The Kerr effect (like the Faraday effect) is an alternative for materials that do not produce any luminescence at the wavelength of interest. Moreover, both Kerr and Faraday effects allow one to study spin dynamics on a broad spectral and thermal range. Compared to Faraday the Kerr effect allows one to study samples outside their transmission region as well as thick samples.

In this paper we illustrate our technique based on the time-resolved dynamical Kerr effect with femtosecond resolution by investigating a GaAsAl/GaAs heterostructure.

1. Theory

The change of the polarization state of the probe pulse upon reflection is described by the following expression [2]

$$\epsilon + i\theta \propto \int dt\, E^*(t)[P^{++}(t) - P^{--}(t)], \tag{1}$$

where ϵ is the Kerr ellipticity and θ is the Kerr rotation. The nonlinear polarization $P^{++} = P_x + iP_y$ ($P^{--} = P_x - iP_y$) is induced by the right (left) circularly polarized light. Eq. (1) is valid if the thickness of the reflecting layer is much smaller than the wavelength of light. This condition is fulfilled in the case of reflection from a quantum well structure.

We assume that low-excitation approximation is applicable [6]. Then, the induced macroscopic polarization $\mathbf{P}(t)$ is related to the wave-vector-dependent interband optical polarization $P_{sj}(\mathbf{k})$ for the transition between the conduction band with spin $s = \pm(1/2)$ and the valence band with angular momentum $j = \pm(3/2), \pm(1/2)$ by the equation

$$\mathbf{P}(t) = \sum_{\mathbf{k},s,j} |\psi_k(0)|^2 \mathbf{d}_{sj} P_{sj}(t, \mathbf{k}), \tag{2}$$

where d_{sj} is the dipole matrix element, $|\psi_k(0)|^2$ is the Sommerfeld enhancement factor. The interband polarization $P_{sj}(\mathbf{k})$ is calculated by solving the semiconductor Bloch equations ($\hbar = 1$)

$$\frac{dP_{sj}(\mathbf{k})}{dt} = \left[-i\varepsilon_{sj}(\mathbf{k}) - \frac{1}{T_2}\right] P_{sj}(\mathbf{k}) + i\Omega_{sj}(\mathbf{k})[1 - n_s(\mathbf{k}) - n_j(\mathbf{k})], \tag{3}$$

$$\frac{dn_j(\mathbf{k})}{dt} = i\sum_s [\Omega_{sj}(\mathbf{k})P^*_{sj}(\mathbf{k}) - \Omega^*_{sj}(\mathbf{k})P_{sj}(\mathbf{k})] - \frac{n_j(\mathbf{k})}{T_1}, \tag{4}$$

and a similar equation for $n_s(\mathbf{k})$. Here $\varepsilon_{sj}(\mathbf{k}) = k^2/2\mu_{sj} + E_g - \omega$, μ is the reduced mass, E_g is the band gap, ω is the central frequency of the laser field, T_1 and T_2 are the phenomenological relaxation times for population and polarization, respectively, $\Omega_{sj}(\mathbf{k})$ is the renormalized Rabi energy.

The laser field has the form $\mathcal{E}(t) = \mathbf{E}(t)e^{-i\omega t}$ with the amplitude

$$\mathbf{E}(t) = \mathbf{e}_+ E_1(t) + e^{i\phi}(\mathbf{e}_+ + \mathbf{e}_-)E_2(t), \tag{5}$$

where $\mathbf{e}_\pm = (\mathbf{e}_x \pm i\mathbf{e}_y)/\sqrt{2}$, $\mathbf{e}_x$, $\mathbf{e}_y$ are the Cartesian unit vectors. In the following discussion we decompose the linearly polarized probe pulse into two circularly polarized pulses. The factor $e^{i\phi}$ describes the relative phase of the pump and probe fields.

We take into account only transitions from the heavy-hole (hh) valence subband to the conduction band. The reasons for that are the large frequency detuning with respect to the light-hole (lh) transitions in the quantum well and the $1/\sqrt{3}$ smaller matrix element of the lh transition. For transitions from hh subband $\mathbf{d}_{(3/2),(1/2)} = -d\mathbf{e}_-$ and $\mathbf{d}_{-(3/2),-(1/2)} = -d\mathbf{e}_+$, where d is the magnitude of the dipole moment. In this model the $\mathbf{e}_+$ component of the probe field only interacts with the $\mathbf{e}_+$ component of the pump field.

We solve Eqs. (3), (4) numerically and calculate the macroscopic polarization $\mathbf{P}(t)$. We seek for a solution which is linear in E_2 and of second order in E_1. In accordance with experimental conditions we average the solution over the relative phase ϕ. This greatly reduces the complexity of the problem. Finally, by using relation (1) we calculate the Kerr ellipticity ϵ and the rotation θ.

2. Samples and experiment

The $Ga_{0.7}Al_{0.3}As/GaAs$ double quantum well structure was grown by MBE on GaAs (001) substrate and growth was monitored by RHEED [5].

The measurement technique uses a differential detection scheme, which is extremely sensitive to small changes in polarization of probe beam and insensitive to laser intensity fluctuations or fast reflectivity changes. By modulating the helicity of the circularly polarized pump beam without changing its intensity one can strongly diminish the effect of the pump beam on the complex refraction index. For the experiment we used Ti-Sapphire laser (100 fs pulses, repetition rate 82 MHz) in the spectral range of 1.44–1.61 eV. The pump and probe pulses were focused on the sample to a spot with a diameter of about 100 μm. The pump fluence was approximately 1 $\mu J/cm^2$. For the study of dynamical Kerr effect the polarization of the pump pulses between two circular polarizations with opposite helicities was modulated using a photoelastic modulator. For the measurements of reflectivity dynamics the intensity of the linearly polarized pump beam was modulated instead of the polarization.

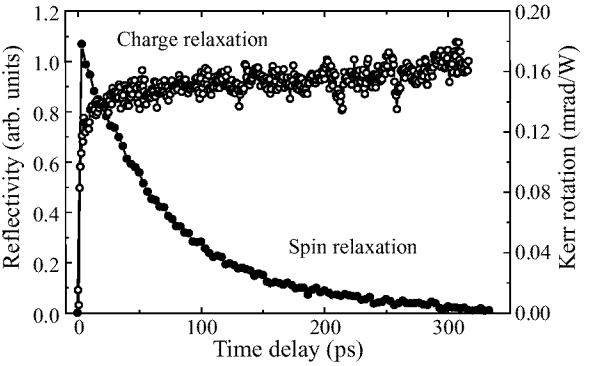

Fig. 1. The dynamics of reflectivity and Kerr rotation, induced by linearly and circulary polarized excitations, respectively.

3. Experimental results and discussion

The dynamics of the reflectivity and the Kerr rotation, which are induced by linearly and circularly polarized excitations, respectively, is presented in Fig. 1 for the central photon energy of the laser pulse at 1.44 eV. One can see that the Kerr rotation dynamics is characterized by an exponential dependence with a decay time of 73 ps. On the other hand, the reflectivity does not relax on this time scale. This is in agreement with the fact that for excited carriers the spin-relaxation time is much shorter than the energy relaxation time. This comparison shows that the dynamical Kerr effect is sensitive to the spin relaxation and insensitive to the population of the excited states, at least in this time regime.

Dynamical Kerr rotation with femtosecond resolution is presented in Fig. 2 for a set of energies in the range 1.45–1.544 eV. The observed effect is characterized by an additional decaying component with a delay time less than 200 fs. Moreover, the dynamical Kerr rotation shows an oscillatory behavior in the region 1.46–1.48 eV.

In Fig. 3 the spectral dependence of the induced Kerr rotation is shown for two delay times $t = 0$ and $t = 500$ fs. In the first case both relaxation components are present. In the second case only one component with the long relaxation time remains. In the inset the similar spectral dependencies for the dynamical reflectivity are presented. One can see that the spectra of the dynamical Kerr effect vary in time.

The fast and long relaxing parts of the induced Kerr rotation have been compared with similar data for undoped and heavily n-doped bulk GaAs. The decay times for these three samples are of the same order of magnitude. The amplitude of the dynamical Kerr effect in the quantum well structure is one order of magnitude larger than in undoped and heavily n-doped bulk GaAs. The fast and long relaxating parts we explain by scattering the spin of holes and electrons, respectively.

The spectral dependencies of the dynamical Kerr effect are completely different from similar data in heavily doped bulk GaAs. The simulation of the experimental data was done by solving the optical Bloch equations (3), (4).

We have found that the nonmonotonous behavior of the Kerr effect as a function of delay time in the vicinity of the excitonic resonance can be explained by the exciton-exciton interaction. Analyzing the behavior of the Kerr rotation and Kerr ellipticity separately we conclude that exciton-exciton interaction reveals not only as the local field effect but also as the interaction induced dephasing time.

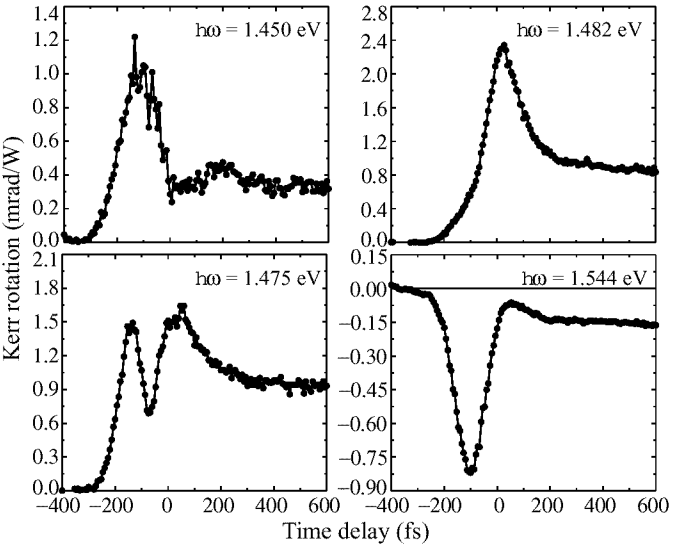

Fig. 2. The dynamical Kerr rotation spectra as a function of time delay in the femtosecond time domain.

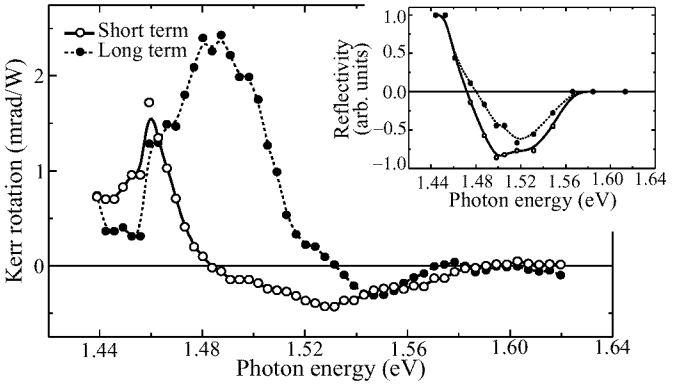

Fig. 3. The spectral dependence of the induced Kerr rotation for two delay times $t = 0$ and $t = 500$ fs.

Acknowledgements

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