Electron dynamics at GaAs-AlGaAs heterojunction studied by ultrafast spectroscopy

A V Leontyev¹, K V Ivanin¹, T G Mitrofanova¹, V S Lobkov¹ and V V Samartsev¹,²

¹Zavoisky Physical-Technical Institute, 10/7 Sibirsky tract 420029 Kazan Russia
²Kazan Federal University, 18 Kremlyovskaya st. 420008 Kazan Russia
E-mail: mailscrew@gmail.com

Abstract. In this letter the electron and spin dynamics at GaAs/AlGaAs heterojunction was studied by ultrafast spectroscopy techniques (photon echo and transient grating studies). Relaxation times and diffusion coefficients of photoexcited electrons and spins were obtained using pure optical setup. The estimated spin diffusion coefficient value of 160 cm²/s is relatively high and comparable to the electron diffusion coefficient of 200 cm²/s. This feature makes GaAs/AlGaAs heterosstructure a promising material for practical application in semiconductor spintronics.

1. Introduction
The coherent excitation of a semiconductor structure leads to a nonlinear polarization which later decays on a subpicosecond timescale because of phase-breaking scattering processes affecting photoexcited carriers and phonons. A possible way to study their interactions involve the transient coherent spectroscopy using ultrashort laser pulses [1],[2]. While the optical dephasing and relaxation experiments can be used to investigate the fundamental static and dynamic properties of condensed matter, they also favour the progress in electronic charge- or spin-based components [3],[4].

The semiconductor heterostructure we studied consists of several layers epitaxially grown on GaAs substrate (figure 1). The heterojunctions of this kind show remarkably high carrier mobilities due to the separation of the free carriers from the parent ionized donors. A large amount of free carriers accumulate at the interface forming a highly populated two-dimensional 10 nm thick electron layer.

2. Transient electron and spin gratings in GaAs / AlGaAs heterostructure
When the two identical pump pulses of wavelength \( \lambda \) simultaneously cross at an angle \( \theta \) in the sample their interference produces a standing wave in the plane of the sample. In case both the pump beams are polarized linearly and parallel to each other, they interfere and generate a spatially periodic electron concentration grating. Note that the internal electric field near the heterojunction area shoves the holes into the bulk GaAs, and thus the observed transient grating is electron-only.
In the simplest model, assuming the main role of relaxation and diffusion in the transient grating destruction, the process is described by [5]

$$\frac{\partial \Delta N(x, t)}{\partial t} = -D \nabla (\Delta N(x, t)) - \frac{\Delta N(x, t)}{T_r},$$  \hspace{1cm} (1)

where $T_r$ is the relaxation lifetime, $D$ is the coefficient of the electron diffusion. In (1) only a linear relaxation lifetime is included and the diffusion coefficient is assumed to be density independent.

The grating period can be calculated as $\Lambda = \lambda / (2 \sin \theta / 2)$, then the electron grating decay rate is expressed in terms of $\Lambda$ by

$$\frac{1}{T_{gr}} = \frac{8\pi^2}{\Lambda^2} D + \frac{2}{T_r},$$  \hspace{1cm} (2)
If the pump beams are cross-polarized the electromagnetic field is spatially distributed like

$$I = I_+ \cos^2(\phi + \pi/2) + I_- \sin^2(\phi + \pi/2)$$

or the superposition of two left and right circularly polarized standing waves shifted with respect to each other by $\Lambda/2$, and the spin direction distribution would follow this pattern. So instead of sinusoidal transient grating of electron population we produce two spin orientation gratings, while the carrier distribution would be uniform.

If the diffusion-driven grating decay plays the substantial role, then the decrease of $\Lambda$ would shorten the grating lifetime. The latter can be extracted through measurement of the diffracted light from a delayed probe pulse. In figure 5 the grating decay rate is plotted versus $8\pi^2/\Lambda^2$. According to (2), the slope of a line approximation is the diffusion coefficient and the intercept is proportional to the electron relaxation rate $1/T_r$.

This fitting procedure yields an electron diffusion coefficient of 200 cm$^2$/s and spin diffusion coefficient of 160 cm$^2$/s at 295 K. The relaxation times were estimated as 3 ns and 50 ps for electrons and spins, respectively.

3. Coherent four-wave mixing spectroscopy of GaAs / AlGaAs heterostructure

Unlike disperse atomic systems in which the optical response can be determined by independent transitions between atomic levels, in semiconductor heterostructures saturation effects of correlations and nonlinear dynamics due to the Pauli principle are most significant.

For the transverse relaxation time evaluation, we follow the degenerate four-wave mixing technique, introduced by Weiner and Ippen [6]. In this setup the delay $\Delta \tau$ between the pump pulses is being altered. The echo signal is emitted and measured in momentum-matched direction.

According to [7], the recorded signal varies with $\Delta \tau$ like

$$I(\tau) \propto \int_0^\infty dt \int_0^\infty dt' f(t' - t)f(t - \Delta \tau)f(t' - \Delta \tau) exp[-2(t + t')/T_2],$$

$$f(t)$$ is the autocorrelation function of laser pulses.
The four-wave mixing measurements and approximation the data by (4) showed the $T_2$ change from 55 to 40 fs caused by the carrier density increase. The power-law fitting of this dependence yielded the exponent of $-0.22 \pm 0.02$ which evidences the presence of Coulomb electron-electron interaction screening. This value differs from -0.3 obtained for bulk GaAs as reported in [8, 9]. One of the crucial points of optoelectronics and optical computing at the present stage of studies is the research of the promising materials possessing the coherent state lifetime as long as possible. An important parameter from the practical point of view is the sample temperature. The room temperature could be the best option as it eliminates the need of the sample cooling. The comparison of the experiment results on bulk GaAs [8] and heterostructure sample in this letter shows that the dephasing time in heterostructure is approximately 3 times higher than that in bulk GaAs in the similar conditions (e.g. 55 fs versus 20 fs at the carrier density of $2 \times 10^{18}$ cm$^{-3}$ and the room temperature).

4. Conclusion
We have presented a four-wave mixing and transient grating experiment on the GaAs/AlGaAs heterojunction on a subpicosecond and picosecond timescale. The electron and spin diffusion coefficients of 200 cm$^2$/s and 160 cm$^2$/s, respectively, were obtained. Since the spin diffusion coefficient is comparable to the carrier diffusion coefficient, the structures of this type are suitable for spin transport applications at room temperature.

Acknowledgments
This study was supported by the Program of RAS Presidium “Quantum mesoscopic and disordered structures”, the Programs of the Department of Physical Sciences of RAS “Fundamental spectroscopy and its applications”, the Program “Leading Scientific Schools” (No NSH.5602.2012.2), and by RFBR grants (No 12-02-31381-mol_a, No 14-02-00041-a, No 14-03-00331-a, No 14-03-31287-mol_a and No 14-02-90000_Bel-a).

References
[1] Weiner A 2011 *Ultrafast Optics* (New York: Wiley)
[2] Ivanin K V, Leontiev A V, Lobkov V S, Nikiforov V G, Salikhov K M, Samartsev V V and Safiullin G M 2009 *Laser Phys. Lett.* 6 644
[3] Wolf S, Awshalom D D, Buhrman R A, Daughton J M, von Molnár S, Roukes M L, Chtchelkanova A Y and Treger D M 2001 *Science* 1 1488
[4] Zutic I, Fabian J and Das Sarma S 2004 *Rev. Mod. Phys.* 76 323
[5] Moss S C, Lindle J R, Mackey H J and Smirl A L 1981 *Appl. Phys. Lett.* 39 227
[6] Weiner A M and Ippen E P 1984 *Opt. Lett.* 9 53
[7] Othonos A 1998 *Appl. Phys. Lett.* 84 1789
[8] Becker P C, Fragnito H L, Brito C H, Fork R L, Cunningham J E, Henry J E and Shank C V 1988 *Phys. Rev. Lett.* 61 1647
[9] Wegener M and Hugel W 2001 *Adv. in Solid State Phys.* 41 89