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Detection of nanoscale acoustic waves gated by transient spin-polarized electrons
ナノスケール音響波検出のスピン偏極電子による変調

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1. Introduction

Manipulation of electron spins is crucial in modern spintronics. Many works have been reported on the optical generation of transient spin populations in semiconductors and on the optical detection of ultrafast dynamics of excited spins[1]. Electron spins can be excited by circularly polarized light, and transient populations of spin-polarized electrons can be detected optically through the Kerr effect[2]. Compared to these well studied spin-light interactions, spin-phonon related effects are less commonly explored. Spontaneous magnetization in ferromagnetic media has been studied by phonon-induced precession of the magnetization on picosecond time scales[3], but little work has been done that connects phonons to transient spins. In this work, we conduct a transient Kerr rotation measurement involving both spins and phonons, and demonstrate phonon detection gated by optically excited transient spin populations.

2. Experiments

The sample contains GaAs/$Al_{0.4}Ga_{0.6}As$ multiple quantum wells (QWs) grown by molecular beam epitaxy on a GaAs (110) substrate. The GaAs (110) well layer thickness is 7.5 nm and the $Al_{0.4}Ga_{0.6}As$ (110) barrier layer thickness is 12.5 nm. On top of 20 periods of this well/barrier combination a GaAs capping layer of thickness of 25 nm is formed. On the sample back surface a Cr film of 150 nm thickness is formed as an optoacoustic transducer.

A standard optical pump-probe setup is used for the measurement, as shown in Fig. 1. A regenerative amplifier seeded by a mode-locked Ti-sapphire laser is used as a light source which generates light pulses of 790 nm central wavelength, 150 fs pulse duration, and 250 kHz repetition frequency.

Some of the light is focused on the back surface of the sample (Cr film) to generate acoustic pulses (strain pump). Some light is delayed and focused on the front surface of the sample (QW side) with circular polarization to excite spin-polarized electrons (spin pump). Yet more light (probe) is de-

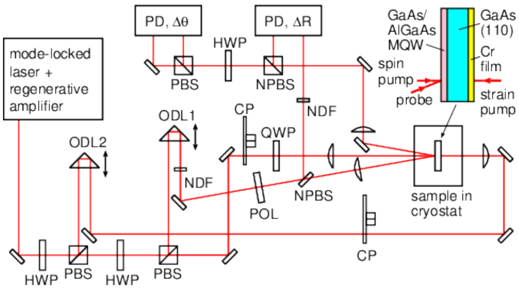

Fig. 1 Schematic diagram of the optical setup. HWP: half wave plate, QWP: quarter wave plate, PBS: polarizing beam splitter, NPBS: non-polarizing beam splitter, POL: polarizer, NDF: neutral density filter, CP: chopper, ODL: optical delay line; PD: photo detector.

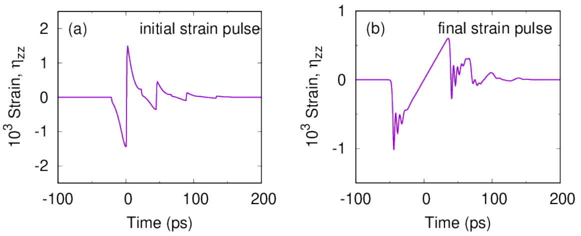

Fig. 2. (a) Calculated strain pulse shape in the GaAs substrate near the Cr film after generation by a pump light pulse. (b) Calculated strain pulse in the GaAs substrate near the QW region.

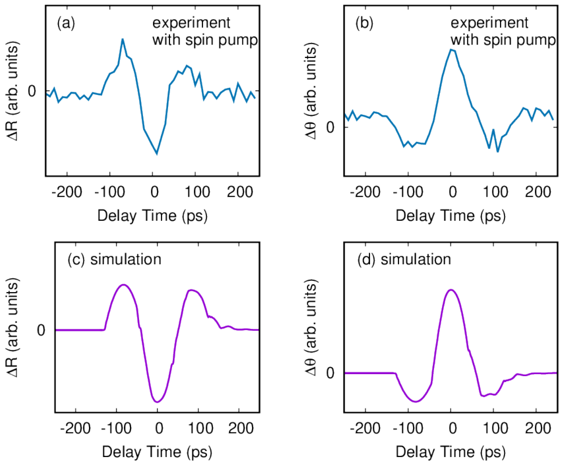

Fig. 3. (a) Experimental result for transient reflectivity change. (b) Experimental transient Kerr rotation. (c) Calculated transient reflectivity change. (d) Calculated transient Kerr rotation.

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layed independently of the spin-pump light, and focused on the front surface of the sample with linear polarization to detect the transient reflectivity change and Kerr rotation.

The sample is placed in an optical cryostat, and the measurement is done at 90 K. At this temperature, the 790-nm wavelength spin-pump light is tuned to the electron transition between the top of heavy-hole band to the bottom of the conduction-electron band in the QWs. This allows the effective excitation of spin-polarized electrons in the QW layers.

The acoustic pulse generated at the Cr film at the back surface by the strain-pump light pulse is distorted because of non-linearity and ultrasonic absorption while it propagates toward the front surface. This distortion process is described by the Korteweg–de Vries equation. Figure 2 (a) shows the calculated strain-pulse shape in the GaAs substrate near the Cr film right after the generation, whereas Fig. 2 (b) shows the strain-pulse in the substrate near the MQWs after propagation.

The strain-pump light is modulated at f_1=1500 Hz and the spin pump at f_2=1200 Hz. The f_1+f_2 frequency components of the probe reflectivity change and Kerr rotation are recorded (heterodyne detection) by varying the delay time between the strain-pump and probe-light pulses. The delay time between the spin-pump and probe light is fixed at 70 ps, which is much shorter than the spin relaxation time of the spin-polarized electrons in the QWs, ensuring the presence of a polarized spins. This heterodyne technique allows one to observe changes simultaneously related to both acoustic strains and excited electron-spin populations.

Figures 3 (a) and (b) show the experimental results for the transient reflectivity change ΔR and Kerr rotation $\Delta\theta$. The origin of the delay time is chosen to be the arrival of the main part of the strain pulse at the sample front surface. To obtain ΔR, reflectivity changes for left-handed and right-handed circular polarization spin-pump light are added. To obtain $\Delta\theta$, the Kerr rotations for left-handed and right-handed circular polarization spin-pump light are subtracted. In this way, any small birefringence or anisotropy effects are cancelled in ΔR and $\Delta\theta$, and one is ensured to observe reflectivity changes not related to the polarity of the excited spin population and only the Kerr rotation caused by the excited spin population.

3. Discussion

To understand the results, the reflectivity change and Kerr rotation are calculated by considering the light scattering caused by the modulation of the permittivity tensor[4,5]. The possible causes of this modulation are the surface/interface displacements, the photoelastic effect, the magneto-optic effect, and higher-order effects related to the strain and the electron-spin population. Since we are using a heterodyne technique, second-order effects concerning the reflectivity change and Kerr rotation need to be considered. The details are described in [4,5]. Figure 3 (c) and (d) show the thus calculated results, which show good agreement with the experiment. The main peak around t=0 is mostly caused by the displacement of the spin-populated layers near the sample front surface, and the smaller peaks around ±100 ps are mostly caused by the displacement of the spin-populated layers near the interface between the MQWs and the substrate. We thus show that the local spin population is probed using strain pulses localized on the nanoscale.

4. Summary

In conclusion, we have demonstrated transient spin-gated optical detection of acoustic pulses. This may be exploited to study the full spatiotemporal dynamics of transient spin-polarized electrons confined on nanometer scales with picosecond temporal resolution. This could also be applicable to spintronic devices.

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