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Bias-dependent spin relaxation in a Spin-LED

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Abstract

We have investigated the bias-dependent spin relaxation in Cu–CoFe–AlO_x–GaAs/AlGaAs-type of Spin-LEDs using microscopic time-resolved magnetization modulation spectroscopy (TIMMS). We observed a significant dependence of the electron spin relaxation time (effects as large as 40%) as a function of applied bias. The additional spin relaxation at non-zero bias is found to scale almost linearly with the injection current, and thereby with the current-induced hole density in the active region. This observation is indicative for a dominant contribution by Bir–Aronov–Pikus (BAP) electron-hole spin-flip scattering. In agreement with this observation, a similar BAP-enhanced spin relaxation shows up at increased laser fluence. From spatio-temporal imaging of spin relaxation, scanning pump and probe beams across the ≈50 μm outside of optical window, we found a significant position dependence (lateral effects) of the spin dynamics.

Keywords: Spin dynamics; Spin injection; Semiconductor devices

1. Introduction

Spintronics aims at developing new generation of devices, in which quantum states based on spin can be carefully prepared and manipulated. Although successful results have been reported [1–4], many problems still exist regarding the efficient spin injection in semiconductors and control over spin relaxation. One of the main problems for an efficient injection of spin polarized current from a magnetic contact into a semiconductor is due to the large conductivity mismatch. Reports on successful injections from II to VI diluted magnetic semiconductors [5], ferromagnetic GaMnAs [6], and across FM/semiconductor Schottky barriers [7] can be considered promising. However, many of these routes are limited to low temperatures, high magnetic fields, or relatively low efficiencies. Another solution for reducing the conductivity mismatch is provided by introducing a thin insulator (oxide) between metal and semiconductor [8]. In order to have a quantitative analysis of electrical spin injection into semiconductors, the configuration of a spin light emitting diode (Spin-LED) [9] can be employed. In such a device spin polarized carriers injected from the contact radiatively recombine in the semiconductor, emitting circularly polarized light. Motsnyi et al. [10] have shown that by applicating a small oblique magnetic field (Hanle effect) in a FM/oxide/semiconductor Spin-LED, the manipulation and assessments of spin injection into of a semiconductor is possible. A spin injection efficiency of 16% and electron spin relaxation times of tens of picoseconds were observed at room temperature. Although this technique provides very valuable information about spin kinetics within the semiconductor, only information on the spin state at the moment of recombination is obtained, and injection efficiency and relaxation times can only be obtained indirectly by fitting the applied field dependence of the optical polarization [10].

In order to obtain more direct information on spin dynamics in a Spin-LED, we performed microscopic time-resolved magnetization modulation spectroscopy (TIMMS) on Cu–CoFe–AlO_x–GaAs/AlGaAs-type of structures. In this technique a circularly polarized pump laser pulse injects electron spin into the active region (GaAs), and an other laser beam probes the spin dynamics. Unlike current-induced photoluminescence, in which the spin relaxation time is obtained in an indirect way, it allows for detailed temporal imaging of electrons and holes separately while moving through the semiconductor device. In particular, we measured the electron spin relaxation time as a function of bias-voltage in the Spin-LED. A significant dependence of the relaxation time was observed as a function of applied bias (effects as large as 40%). As will be seen later from our experimental results, the spin relaxation is found to scale almost linearly

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with the injection current, and thereby with the current-induced hole density in the active region. This observation is indicative for a dominant contribution by the Bir–Aronov–Pikus (BAP) mechanism, where the exchange interaction between electron and hole spins causes electron spin flipping.

Our experimental set-up not only allows for a detailed temporal imaging, but also a spatial imaging of spin dynamics. Scanning pump and probe across the Spin-LED, we observed an enhanced spin relaxation in a region of tens of micrometers outside the optical window, as indicative for a bias-driven enhanced hole density in that region as well.

2. Experimental

The Spin-LED used in the spin dynamics measurements was grown by molecular beam epitaxy on a (0 0 1) *p*-GaAs substrate: 2.75-μm *p*-GaAs buffer layer ($p = 2 \times 10^{19}$ cm^{-3}), 200-nm *p*-$Al_{0.30}Ga_{0.70}As$ ($p = 1 \times 10^{18}$ cm^{-3}), 100-nm *p*-GaAs ($p = 1 \times 10^{18}$ cm^{-3}) active region and 20-nm $Al_{0.20}Ga_{0.80}As$ (undoped). Immediately after the growth, the sample was transferred into the sputtering machine for the fabrication of the tunnel injector. The oxide layer was deposited in a two-step process, which facilitates a full oxidation of the Al and reduces the chance on pinholes. First, a 1 nm thin Al layer is sputtered and naturally oxidized in a controlled oxygen atmosphere at 140 Torr. After sputtering and oxidizing of the first Al layer, a second Al layer was sputtered and oxidized, followed by the deposition the ferromagnetic stack. After fabrication of the AlO_x, the 10-nm $Co_{90}Fe_{10}$/5-nm Cu ferromagnetic stack was sputtered by dc-magnetron sputtered in the same vacuum chamber. The devices were packaged and contacted using Au contacts to the backside of the substrate and to the front FM electrode, leaving a window for optical accesses. The easy magnetization axis of the ferromagnetic film is in-plane. Previously, spin injection efficiencies of 16% at room temperature were reported for these spin-LEDs [10].

The optical pump-probe technique for time-resolved magnetization modulation spectroscopy (TIMMS) has been described in detail before [11]. The experimental setup is based on a femtosecond Ti:sapphire laser that generates pulses of 150 fs, at a repetition rate of 80 MHz. Laser pulses are split in high (pump) and low (probe) intensity pulses that are focused by a 12 cm lens to overlapping spot with a diameter of ≈40 μm at the sample and the relative delay between them is controlled by a mechanical delay line. The high intensity pump pulse is used to spin-selectively excite electrons in the Spin-LED. The time-delayed, weaker probe pulse is then used to measure the magneto-optical Kerr rotation. Spin-selective excitation is achieved by guiding the pump pulses through a photoelastic modulator (PEM), introducing a circular polarization with a handedness oscillating at 50 kHz. The probe pulses are modulated by a mechanical chopper, operating at a frequency of typically 80 Hz. The measured Kerr signal is then led through a series of two lock-in amplifiers, of which the first one is set at the modulation frequency of the PEM and the second one at the frequency of the chopper in the probe beam. Because of this double modulation any possible signal due to pump light reaching the detector is completely suppressed. All the measurements were performed at room temperature and with the same laser wavelength λ = 770 nm (1.61 eV), i.e. the photon energy is above the bandgap of GaAs (1.43 eV) at room temperature [12].

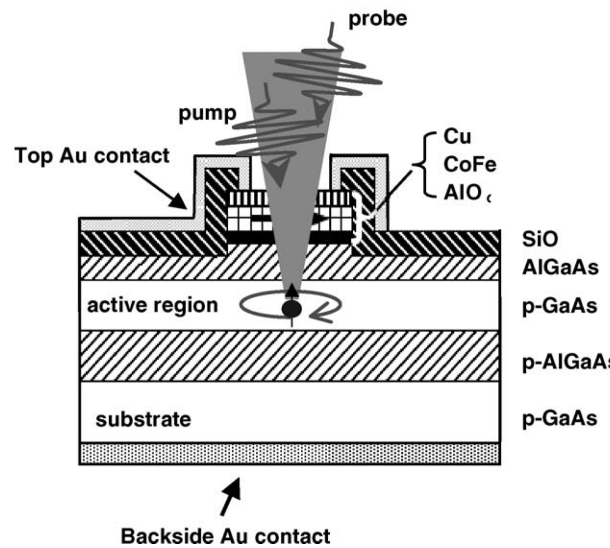

Fig. 1. A schematic representation of spin-LED, showing the top Au contact with the optical window. In a TIMMS experiment, a photo-elastic modulator (PEM) modulates the pump between left and right-handed circular polarization, and another laser beam probes the spin-dynamics after arrival of the pump pulse.

As we can see in Fig. 1, spin is optically injected inside the active region (100 nm *p*-GaAs) of the Spin-LED, after laser light passes through the optical window, i.e. the ferromagnetic film on top causes some additional absorption, but does not participate in optical spin injection. The film of $Al_{0.20}Ga_{0.80}As$ is almost transparent ($E_{gap} = 1.67$ eV) [13] for our laser photon energy (1.61 eV) and does not interfere in our measurements.

3. Results and discussion

Fig. 2(a) displays the time-resolved TIMMS signals from the Spin-LED for different bias voltage. Note that the enhancement of the applied bias (0–2.43 V) resulted in a faster electron spin relaxation by ≈ 30%. From these results we plot the electron spin relaxation rate as function of bias (Fig. 2(b)) after fitting the curves by a single exponential decay. The bias-dependent spin relaxation is nonlinear and is very similar to the typical I–V response in the Spin-LED, shown in Fig. 2(b) (inset). This means that *the spin relaxation rate increases linearly with current*. In the next experiment we focus on the laser fluence contribution to the spin relaxation. Fig. 3 shows the spin relaxation rate versus laser fluence for two different applied bias voltages (0 and 2.43 V). *The spin relaxation rate is found to increase linearly with laser fluence*, for both bias voltages.

For a proper analysis we should be aware of the fact that the time-resolved TIMMS signals depend both on the spin scattering time, τ_s, and the electron-hole recombination time (τ). In order to extract the genuine spin scattering time it is necessary to correct for the electron-hole recombination, according to $\tau_s^{-1} = T_s^{-1} - \tau^{-1}$. We performed transient reflection experiments to extract τ. Although these transients were difficult to