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Electric-field effects in optically generated spin transport

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ABSTRACT

Transport of spin-polarized electrons in semiconductors is studied experimentally. Spins are generated by optical excitation because of the selection rules governing optical transitions from heavy-hole and light-hole states to conduction-band states. Experiments designed for the control of spins in semiconductors investigate the bias-dependent spin transport process and detect the spin-polarized electrons during transport. A strong bias dependence is observed. The electric-field effects on the spin-polarized electron transport are also found to be depended on the excitation photon energy and temperature. Based on a field-dependent spin relaxation mechanism, the electric-field effects in the transport process are discussed.

1. Introduction

Recently, there has been an increasing interest in the emerging field of spin electronics [1,2] or spintronics [3,4], or spin physics in broader sense [5], where the electron spin degree of freedom is exploited and new semiconductor devices are proposed. One of the important requirements necessary in developing semiconductor spintronic devices is the transporting spin-polarized carriers over reasonable distances without spin-flipping or spin relaxation in a semiconductor.

However, the generation (or injection) of spins is a prerequisite for the study of spin transport. The generation of electron spins in a semiconductor has successfully been obtained by optical excitations [3]. For optical excitation of bulk zinc-blende semiconductors with photon energy just above the band gap (E_g), because of the selection rules governing optical transitions from heavy-hole, or light-hole, states to conduction band states, right circular polarized light (RPL) generates a density of spin-down electrons ($N_\downarrow$) which is three times the density of spin-up electrons ($N_\uparrow$), and vice versa for left circularly polarized light (LPL) [6,7]. Since optically excited hole spin relaxation is extremely fast ($\leqslant 100$ fs), their polarization is effectively zero and need not be considered. Hence the initial value $p(0,0)$ of electron spin polarization, defined as

$$p(\vec{r},t) = \big(N_\downarrow(\vec{r},t) - N_\uparrow(\vec{r},t)\big)/\big(N_\downarrow(\vec{r},t) + N_\uparrow(\vec{r},t)\big), \tag{1}$$

generated by a RPL (LPL) beam in a zinc-blende semiconductor is $+0.5$ (-0.5), i.e. 50%. Optical excitation with RPL (LPL) generates spins along the direction parallel (antiparallel) to the direction of the light propagation. By obeying the same selection rules the reverse is also possible that the recombination of spin polarized charge carriers results in the emission of circularly polarized light.

In the present investigation, we studied experimentally the transport of spin-polarized electrons in semiconductors. Spins are generated by optical excitation as discussed above. Experiments aimed for the optical manipulation of spins in semiconductors investigate the bias-dependent transport process and detect the spin-polarized electrons during transport. A strong bias dependence is observed. The electric-field effects on the spin-polarized electron transport are also studied in dependences of excitation power as well as of excitation photon energy. The field effects in the transport process are discussed in details.

2. Experimental details

2.1. Device fabrication and characterization

Investigated samples were fabricated on moderately doped GaAs with different Si-doping densities. Prior to contact deposi-

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tion, the substrates (A: 1.4×10^{16} cm^{-3}, B: 1×10^{17} cm^{-3} and C: 5×10^{17} cm^{-3}) were cleaned using conventional organic solvents. The native surface oxide was then removed using HCl : H_2O (1 : 1 vol.) followed by a de-ionized water rinse and blown dry with nitrogen before loading the substrates in the evaporation chamber. Au(100 nm)/Ge(40 nm)/Pd(10 nm) contacts were deposited on the substrates, with Pd layers adjacent to the GaAs substrates, using an e-beam evaporator with a base pressure of $\sim 5 \times 10^{-8}$ Torr. The contact metallization was annealed in a tube furnace in flowing nitrogen at 180 °C for 1 h to achieve reliable or ohmic contacts with low contact resistance. Gold wires were bonded from the sample-holder to the contact pads. The specific contact resistivity was assessed using transmission line model [8]. The doping density-dependent contact resistivity is shown in Fig. 1. As can be seen, the resistivity increases with decreasing doping density and values are within a range between 1.9×10^{-6} and 8×10^{-6} $\Omega\,$cm^2. The results confirm that the devices contain transparent contacts.

2.2. Experimental setup and measurements

For optical excitation, a mode-locked Ti:sapphire laser (which generates ps pulses at 76 MHz repetition rate) was used. A neutral density wheel (NDW) was used to vary the optical power. The polarization of the optical beam was modulated using a photo-elastic modulator (PEM) at a lock-in reference frequency of 42 kHz. The laser beam (LB) was focused on to a ~ 90 μm (FWHM) spot of the sample with a lens (L). Care was taken not to illuminate any of the electrical contacts to avoid the generation of any artefacts. To check that the beam hits the sample on the desired location, a microscope was used. The lens was designed for minimum spherical aberrations. The spot size was measured by knife-edge scans and the spatial (or the sequence focus) profile of the pulse was found to be Gaussian. A regulated electric power supply was used as a bias source. The signal was measured by a lock-in amplifier coupled to a computer. The sign of the signal was found to be reversed with reversing the bias field. A schema of the experimental setup along with an illustration of the sample geometry and the excitation scheme is shown in Fig. 2. To show the temperature dependence, we measured the signal at liquid helium, liquid nitrogen and room temperatures. All other experiments were performed at room temperature. The room temperature mobility and excited carrier density were estimated for the three samples. They are (5300 cm^2/V s; 6×10^{17} cm^{-3}), (4100 cm^2/V s; 2×10^{18} cm^{-3}) and (3200 cm^2/V s; 5×10^{18} cm^{-3}) for A, B and C respectively.

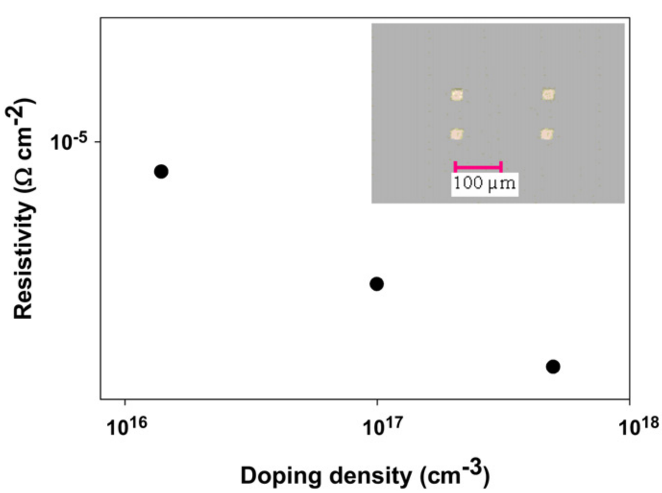

Fig. 1. Contact resistivity as a function of doping density. The insert shows a photograph of the sample device (expanded view).

3. Results and discussion

We study the spin transport process and investigate the effects of a longitudinal electric field (field effects) on the spin-polarized electrons generated by a circularly polarized light in semiconductors [9]. Our experiment observes the effects resulting from nonequilibrium magnetization induced by the spin-carrier electrons [10] accumulating at the transverse edges of the sample.

In a semiconductor, if two spin populations are unequal, for example, current carriers contain more spin-up electrons than spin-down electrons, there would be more electrons scattered to the right than to the left (asymmetries in scattering) via skew-scattering [11] and side jump [12] in the presence of spin–orbit interaction. This leads to both spin [13] and charge [14] accumulations in the transverse direction of the sample. When the photo-induced spin-polarized carriers are dragged by an external bias in a sample, an optically spin-induced transverse voltage is observed. The voltage is a measure of the net charge accumulation on the transverse edges of the sample for the generated spin-polarized electrons.

Fig. 3 shows the bias-field dependence of the voltage for samples A, B and C excited with the power $P_{ex} = 5$ mW and photon energy (E_{ex}) having an excess $\Delta E_{ex} = 100$ meV, where

$$\Delta E_{ex} = E_{ex} - E_g = \hbar\omega - E_g. \tag{2}$$

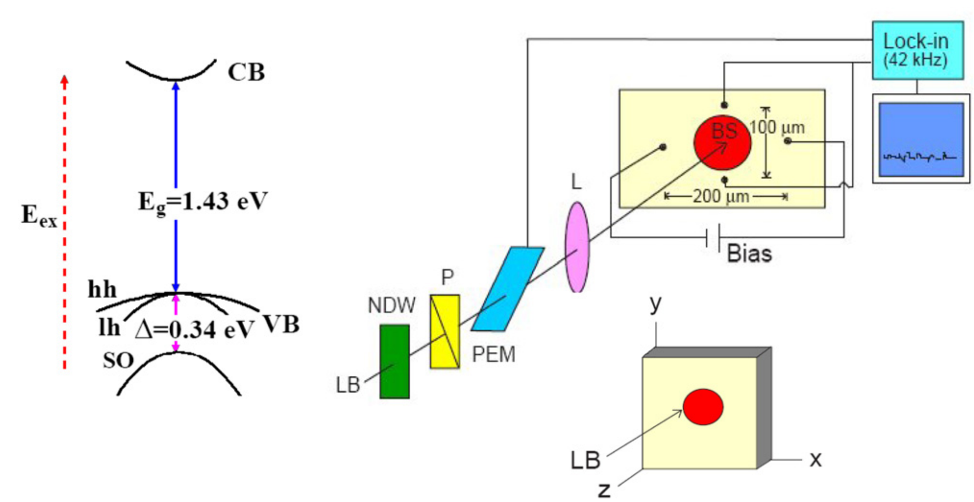

Fig. 2. A schema of the experimental setup along with an illustration of the sample geometry and the excitation scheme.