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Relaxation of photoinjected spins during drift transport in GaAs

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We studied the transport of photoinjected spins in GaAs by time-resolved photoluminescence measurements. At low temperatures, the spin polarization after drift transport of 4 μm is found to decrease as the applied electric field E increases to a few kV/cm, and it disappears when E exceeds 3 kV/cm. The origin of the field-dependent spin relaxation is discussed. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1512818]

Stimulated by the observation of long spin coherence time in semiconductors,[1] considerable research efforts have been devoted to the injection and transport of spins in semiconductors in order to harness the spin degree of freedom of carriers in semiconductors. Recent progress in epitaxial growth of magnetic semiconductors and ferromagnetic metals on nonmagnetic semiconductor light emitting device structures has enabled us to achieve electrical injection and optical detection of spin-polarized currents in semiconductors.[2–7] Adding to these, observations of macroscopic propagation of spin polarization and coherence in semiconductors[8–10] have encouraged implementation of devices based on manipulation of the coherent spin states for solid-state quantum information technology.[11] Theoretical studies of spin-polarized transport in diffusive and ballistic regimes have also been developed in a various class of semiconductor-based heterostructures.[12–15]

For high speed transfer of spin information, electron spins have to be subjected to high external electric fields. Although influence of low electric fields ($<10^2$ V/cm) on coherent spin transport has been reported,[9] little is known about the effect of high electric fields ($>10^2$ V/cm) on the length scale of spin transport. Here we report a study on the spin-polarized electron transport in GaAs under applied electric fields. We show that with a moderate electric field (a few kV/cm), depolarization of photoinjected spins occurs during the drift transport in GaAs.

The dynamics of the spin transport in semiconductors has been measured by a time-resolved, optical injection and detection method, similar to the one employed in Ref. 8. As shown in the inset of Fig. 1, a thick GaAs layer (5 μm) grown on an (In,Ga)As quantum well (QW) is irradiated by a circularly polarized light. Spin-polarized electrons and holes created near the surface of GaAs ($\leqslant 1$ μm) are separated by an external electric field along the growth direction. When a forward bias is applied, electrons are driven toward the QW, where they recombine with spin-unpolarized holes supplied from the back p-AlGaAs/p-GaAs. By analyzing the polarization of photoluminescence (PL) from the QW, we evaluate the degree of electron spin polarization after drift and/or diffusion through the bulk GaAs.

The sample was grown by molecular beam epitaxy (MBE). It consists of, from the top side, a 5-μm-thick undoped GaAs layer, a 10-nm-thick $In_{0.13}Ga_{0.87}As$ QW, a 400-nm-thick p-AlGaAs, and p-GaAs buffer grown on a p-GaAs (100) substrate. The top Schottky electrode was formed by deposition of a thin semitransparent Au film. For optical excitation, we used a mode-locked Ti:sapphire laser which generates 110 fs pulses at 76 MHz repetition rate. The polarization of excitation light was altered between right (σ^+) and left (σ^-) circular polarization, and only the σ^+ component of the PL is detected. The PL polarization P is defined as $(I_+ - I_-)/(I_+ + I_-)$, where $I_\pm$ are the intensities

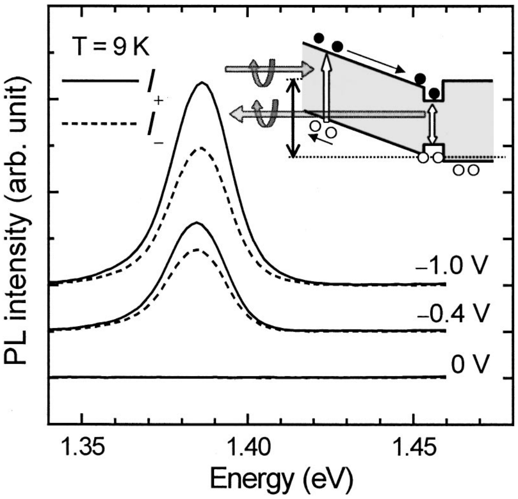

FIG. 1. Typical photoluminescence spectra of 5 μm GaAs/10 nm InGaAs/p-AlGaAs measured at 9 K with an applied bias voltage of 0, -0.4, and -1.0 V. The inset schematically shows the optical injection and detection method of spin-polarized electron transport.

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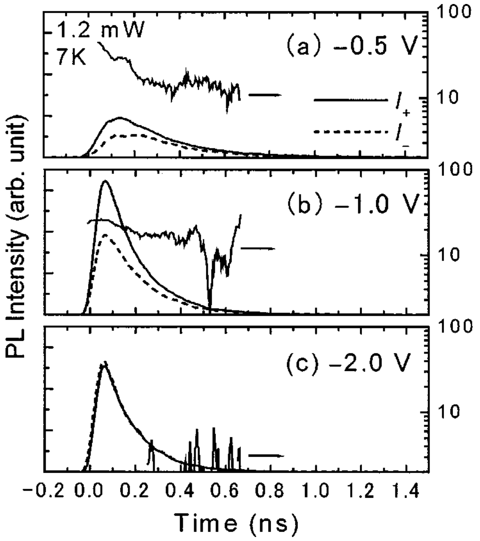

FIG. 2. Time evolutions of $I_\pm$ and P measured at 7 K when the bias voltage is (a) -0.5, (b) -1.0, and (c) -2.0 V. The excitation energy E_{ex} is 1.58 eV and the excitation power is 1.2 mW.

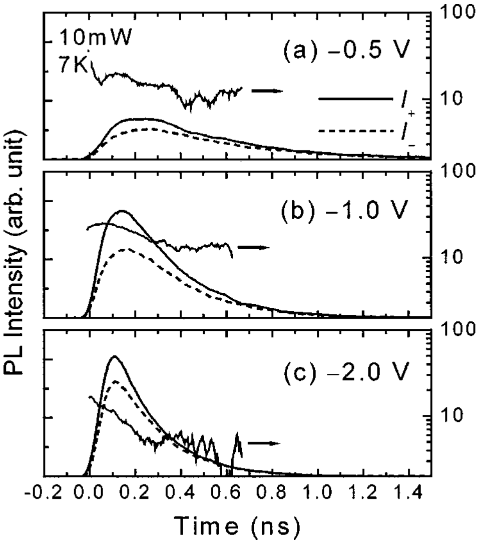

FIG. 3. Time evolutions of $I_\pm$ and P measured at 7 K when the bias voltage is (a) -0.5, (b) -1.0, and (c) -2.0 V. The excitation energy E_{ex} is 1.58 eV and the excitation power is 10 mW.

of the σ^+ component of the PL when the sample is excited by $\sigma^\pm$ polarized light. The excitation photon energy E_{ex} is tuned at or slightly above the energy gap of GaAs E_g $(=1.515\ \text{eV})$. Time-resolved measurements are done by a streak camera.

Figure 1 shows the typical bias voltage (V) dependence of the time-averaged PL spectra ($I_\pm$) measured at 9 K. No PL is observed at zero- and reversed bias conditions at low temperatures, indicating that the direct excitation of the QW is negligible. When the applied forward bias exceeds a threshold voltage $(-0.5\ \text{V})$ corresponding to the flat band condition, a clear PL is detected. There is no observable peak shift in PL spectra up to $V=-2.0$ V.

We then measured the temporal evolution of $I_\pm$ at $E_{\text{ex}} = 1.46$ eV (below E_g) at 10 K, i.e., direct excitation of spin-polarized electrons in the (In,Ga)As QW, to evaluate the effect of processes occurring in the QW. The recombination lifetime τ_r and the electron spin relaxation time τ_s of the (In,Ga)As QW are found to be 200 ± 50 and 400 ± 200 ps, respectively, and we observed no V dependence of τ_r and τ_s up to -2.0 V. Thus the V dependencies of $I_\pm$ and P with $E_{\text{ex}}\geqslant E_g$ observed in Fig. 1 cannot be attributed to the bias-voltage dependent processes in the QW.

We observed no significant dependence of P on E_{ex} between 1.51 and 1.61 eV (not shown), which indicates that the effect of initial spin depolarization during energy relaxation after excitation is negligible. The time-averaged P is about 22% at maximum, while the selection rule predicts $P = 50\%$. The low P of the PL from the QW is believed to be due to the spin relaxation occurring in the energy relaxation process from GaAs into the QW and in the QW via electron–hole exchange interaction.[15]

Figure 2 shows the traces of $I_\pm$ at several bias voltages V measured at 7 K. Here $E_{\text{ex}}=1.58$ eV and low excitation power (1.2 mW) was used. When $V=-0.5$ V (flat-band condition), the rise and fall of $I_\pm$ is slow because of the low electric field in the GaAs layer [Fig. 2(a)]. P remains almost constant over >0.6 ns, indicating that the spin polarization is transferred without relaxation during transport. As the forward bias increases to $V=-1.0$ V [Fig. 2(b)], the decay time of $I_\pm$ becomes shorter (200 ps) and remains constant below -1.0 V. The 200 ps decay time compares well with the separately measured recombination lifetime of the (In,Ga)As QW. On the other hand, the trace of P at $V=-1.0$ V is almost unchanged compared with that at $V=-0.5$ V. This indicates that the spin polarization of electrons can be conserved during the drift transport in GaAs in a moderate electric field.

As the electric field increases further, however, the behavior of P changes drastically: As shown in Fig. 2(c), at $V=-2.0$ V, the difference between I_+ and I_- is no longer resolved even at the initial rise. This suggests that the spin polarization has already been relaxed before the photoinjected electrons reach the QW.

Figures 3(a)–3(c) shows the time-resolved $I_\pm$ measured at 7 K with a higher excitation power of 10 mW. As the excitation intensity increases, the reduction of the effective electric field for the photoinjected electrons occurs due to the screening effect.[8] Compared to the results in Fig. 2, one can see that the decay of $I_\pm$ becomes slower at the same external bias voltage. Although reduced, P of 8% is clearly seen at $V=-2.0$ V [Fig. 3(c)], showing the effect of screening.

Figure 4 shows the bias voltage dependence of P measured at 6–40 K with the excitation intensity of 10 mW. It is seen that P decreases significantly at $V<-1.0$ V, corresponding to the nominal (unscreened) electric field E of about 1 kV/cm in bulk GaAs [calculated from $-(V + 0.5\ \text{V})/5\ \mu\text{m}$, where the additional 0.5 V is the threshold for PL]. At $E=3.5$ kV/cm, P is completely quenched at temperatures below 30 K.

A possible scenario for the enhanced spin depolarization under an applied electric field of a few keV is the depolarization due to heating of the electron temperature. The background impurity (carbon) level of the present sample is less than $10^{15}\ \text{cm}^{-3}$ (measured in undoped bulk GaAs grown in the same MBE system), thus the electron mobility exceeds $10^5\ \text{cm}^2/\text{Vs}$ at low temperatures. Then, at a few kV/cm over a distance shorter than 5 μm, electrons are accelerated over

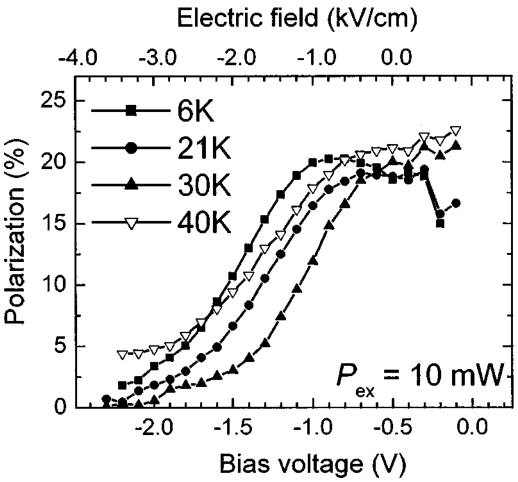

FIG. 4. PL polarizations measured at various temperatures are plotted as a function of the bias voltage.

the velocity, where the electron temperature increases sharply due to the energy-independent nature of the dominant energy relaxation process [longitudinal polar optical (LO) phonon scattering].[16] The resulting high electron temperature leads to a much enhanced D'yakonov–Perel' (DP) spin relaxation. The DP spin relaxation occurs due to the spin precession about an effective magnetic field induced by the lack of inversion symmetry and the presence of a spin-orbit coupling,[17] and the DP spin relaxation time is inversely proportional to the cube of the electron kinetic energy. Simulation based on this scenario is in agreement with the present experiment.[18] The absence of strong temperature dependence in Fig. 4 is due probably to the nature of the scattering process; the scattering by LO phonons does not depend critically on temperature when electrons are hot.[16] The present result is qualitatively different from that of Ref. 8, in which *P* remains almost unchanged up to 6 kV/cm under similar experimental conditions, most probably because of the higher mobility of electrons.

In conclusion, we investigated spin relaxation of photoinjected electrons during drift transport in GaAs by time-resolved PL polarization measurements. The photoinjected spins can traverse without losing their initial orientation for 4 μm scale as long as the electric field E is below a threshold value of 1 kV/cm. Above 1 kV/cm, however, spin depolarization is considerably enhanced most probably due to the enhanced DP spin relaxation as a result of the heating of the electron temperature.

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