Photo-Induced Spin Dynamics in Semiconductor Quantum Wells

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Abstract We experimentally investigate the dynamics of spins in GaAs quantum wells under applied electric bias by photoluminescence (PL) measurements excited with circularly polarized light. The bias-dependent circular polarization of PL ($P_{PL}$) with and without magnetic field is studied. The $P_{PL}$ without magnetic field is found to be decayed with an enhancement of increasing the strength of the negative bias. However, $P_{PL}$ in a transverse magnetic field shows oscillations under an electric bias, indicating that the precession of electron spin occurs in quantum wells. The results are discussed based on the electron–hole exchange interaction in the electric field.

Keywords Photoluminescence · Spin transport · Exchange interaction

Introduction

Possibility of using information carried by the spin of the electron in electronic devices, in addition to its charge, has gained a lot of attention since the discovery of long spin lifetimes in semiconductor structures [1], leading to the growth of the field spintronics [1–3]. This may lead to new devices beyond well-established storage or memory applications, already implemented as giant magnetoresistance (GMR) read-heads and nonvolatile magnetic RAM (MRAM) [2].

One of the major hurdles in the development of spintronic devices has been the problem of efficiently injecting spin-polarized carriers into a semiconductor, transporting them over reasonable distances without spin-flipping and then detecting them. Much effort [3] has thus been spent in understanding the transport and dynamics of spins and the generation/injection and detection of spin currents in semiconductors. Generation of spin polarization usually means creating a nonequilibrium spin population. This has been achieved in various ways, e.g. by optical techniques, or by magnetic semiconductors or ferromagnetic contacts, with varying degrees of success [3]. Although the detection of spin current in semiconductors was previously been achieved mainly through optical methods [1], an electrical means of detecting spin current has been obtained recently [4–6]. Despite many efforts and substantial progress, a further major obstacle to the practical implementation of spintronics is the lack of a proper understanding of spin transport and dynamics in semiconductor-based heterostructures [3].

In this paper, we focus on spin dynamics in GaAs quantum wells (QWs) under applied electric bias by photoluminescence (PL) measurements excited with circularly polarized light [7–9]. We study the bias-dependent circular polarization of PL ($P_{PL}$) with and without magnetic field. The $P_{PL}$ without magnetic field is found to be decayed with an enhancement of increasing bias. However, $P_{PL}$ in a transverse magnetic field shows oscillations under an applied bias, indicating that the precession of electron spin occurs in QWs. The results are discussed by exploring the possible roles played in the observed phenomena.
Experimental

The samples studied in the present investigation were GaAs double QWs (10 nm) separated by a thin (~20 nm) A10.3Ga0.7As barrier. The samples were grown on the Si-doped GaAs substrate. For the application of the external bias (field normal to the heterostructure layers), the top surface of the sample was coated with a semitransparent electrode (Au). We excited the sample by circularly polarized ps pulses of a tunable Ti: sapphire laser with a repetition rate of 76 MHz and measured the PL both in zero magnetic field and in a magnetic field (5 T) aligned perpendicular to the growth axis of the structure (Voigt geometry) using a streak camera. The PL was excited directly to the exciton absorption band and was detected with the small long-wavelength shift to minimize the polarization losses [10, 11].

Results and Discussion

The circularly polarized PL was studied as a function of the electric bias and of the external magnetic field. The PL was measured in the left and right circular polarizations under right circularly polarized excitation. In the absence of the magnetic field, the PL intensities with the same and opposite circular polarization for −2.5 V bias are shown in Fig. 2. Figure 3 shows the kinetics of the degree of circular PL polarization. As seen, the PL polarization kinetics of the QWs substantially depends on bias. In the absence of the bias (Fig. 3a), the kinetics of the $P_{PL}$ has a small slow component with the decay time 1 ns dominated by a fast component characterized by the decay time below 0.1 ns, in consistence with other observations [12, 13]. When a negative bias is applied to the top electrode of the sample, the amplitude of the slow component increases and, for the applied bias, this component predominates.

One more mechanisms of the relaxation of the excitonic spin oriented by the light might be possible. Relaxation can result in the PL depolarization due to a flip of the exciton spin as a whole or independent flips of the electron and hole spins [14]. In the first case, the decay time of the $P_{PL}$ is directly determined by the exciton spin relaxation rate [15]. If the carrier spins relax independently, the fast flip of the hole spin does not affect the $P_{PL}$. In this case, the decay of the $P_{PL}$ is controlled by the relaxation of the long-lived electron spin. The above analysis reveals that the bias-induced changes in the polarized PL kinetics are related to transition from dynamics of the exciton spin to that of independent electron and hole spins. In the absence of the bias, the exchange coupling exceeds the spin–phonon
interaction [16], and the main relaxation mechanism is
given by the exciton spin flips, as mentioned above.

In the presence of the applied bias, the electric field
reduces the electron–hole exchange coupling by spatially
separating the charges, and as a result, the interaction of the
hole spin with phonons becomes stronger than the
exchange interaction. This leads to a breakage of the
interference of the states of the exciton fine structure split
by the combined action of the magnetic field and exchange
coupling induced by the external electric field [23, 24]. As
Fig. 4a demonstrates, the $P_{PL}$ varies with time in a rather
complicated way of the PL polarization kinetics [25],
reflecting superposition of the beats at several frequencies.
From the above discussion, one can conclude that appli-
cation of the bias to the QWs weakens the exchange
interaction between the electron and hole spins.

Figure 4 shows the $P_{PL}$ in the presence of the applied
magnetic field for zero and $-2.5$ V bias. As can be seen, the
effect of the bias on the polarized PL kinetics of the QWs
appears to be more pronounced in the presence of the
transverse $H$. For the $-2.5$ V bias, the polarization kinetics
shows distinct oscillations symmetric with respect to the
horizontal axis. An analysis of the $P_{PL}$ dynamics in $H$ gives
additional evidence for the exchange interaction suppression
in an external electric field. In the presence of the bias, the
hole spin rapidly relaxes and its projection onto the direction
of observation varies. Being uncoupled with the hole spin,
the electronic spin may freely precess around the magnetic
field direction. The projection of the electron spin onto the
direction of observation oscillates in time with the Larmor
frequency $\omega_{L} = g_{B} H / h$ [18], where $g_{B}$ is the Bohr mag-
teton, $g$ is the electron- $g$ factor and $h$ is the reduced Planck
constant. The $P_{PL}$ should oscillate between $+1$ (100%) and
$-1$ with the same frequency [19] because, when the hole
spin has no preferential orientation, this quantity is deter-
mined only by the projection of the electron spin.

As can also be seen from Fig. 4, the oscillation ampli-
tude is initially equal to $\sim 0.8$ and slowly decays with time.

The data can be fitted by the exponentially damping harmonic function $P_{PL} = P_{PL}^{0} \exp(-t/\tau) \cos(\omega_{L} t)$, which gives
$\omega_{L} = 0.1$ THz and the decay time $\tau = 200$ ps for the
$-2.5$ V bias and $H = 5$ T. The obtained oscillation fre-
cency $\omega_{L}$ corresponds to the value $g = 22.7 \times 10^{-2}$. This
agrees with the experimental as well as theoretical esti-
mates of the transverse electron $g$-factor in GaAs QWs
[20–22].

In the absence of the bias, there involves only the
behaviour of the exciton spin as a whole. The $H$ mixes the
excitonic states, and as a result, the right circularly polar-
ized light becomes capable of exciting several states. The
kinetics of the polarized PL is controlled here by the
interference of the states of the exciton fine structure split
by the electric field. The results were discussed based on the electron–hole exchange interaction in the electric field.

### Conclusion

The dynamics of spins in GaAs QWs under applied electric
bias has been experimentally investigated by PL measure-
ments. The bias-dependent $P_{PL}$ with and without
magnetic field was studied. The $P_{PL}$ without magnetic field
was found to be decayed with an enhancement of
increasing negative bias. However, $P_{PL}$ in a transverse
magnetic field showed oscillations under an applied bias.
The oscillation amplitude was found to be increased with
increasing the strength of the bias. The results were dis-
cussed based on the electron–hole exchange interaction in the electric field.

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