Spin transport of indirect excitons in GaAs coupled quantum wells

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Spin transport of indirect excitons in GaAs/AlGaAs coupled quantum wells was observed by measuring the spatially resolved circular polarization of the exciton emission. The exciton spin transport originates from the long spin relaxation time and long lifetime of the indirect excitons.

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Spin transport in semiconductors includes a number of interesting phenomena in electron transport, such as current-induced spin orientation (the spin Hall effect) [1, 2, 3], spin-induced contribution to the current [4], spin injection [5], and spin diffusion and drag [6, 7, 8, 9]. Besides the fundamental spin physics, there is also considerable interest in developing semiconductor electronic devices based on spin transport, which may offer advantages in dissipation, size and speed over charge-based devices, see [10, 11] and references therein. It was found that the spin relaxation time of the indirect excitons is orders of magnitude longer than for regular excitons in single QW. In GaAs single QW, the spin relaxation time of the indirect excitons is typically limited by the electron-hole exchange interaction [13, 14, 15].

Heavy hole excitons with $S_z = +1$ (-1) emit $\sigma^+$ ($\sigma^-$) polarized light while excitons with $S_z = \pm 2$ are optically inactive. The dynamics of the polarization of the exciton emission $P = (I_e - I_h)/(I_e + I_h)$ is determined by the recombination and spin relaxation processes. For an optically active heavy hole exciton with spin $S_z = \pm 1$, spin flip of either electron or hole would transform the exciton to an optically inactive state with spin $S_z = \pm 2$, Fig. 1a. Therefore, these processes do not cause the decay of the emission polarization. The polarization decays when both the electron and hole flip their spins. This occurs in the two-step process due to the separate electron and hole spin flips and the single-step process due to the simultaneous flipping of the spin of both electron and hole. The rate equations describing these processes [13, 14] yield the polarization of the exciton emission $P = \tau_p/(\tau_p + \tau_e)$, where $\tau_e^{-1} = 2(\tau_e + \tau_h)^{-1} + \tau_{ex}^{-1}$ is the relaxation time of the emission polarization, $\tau_{ex}$ is time for exciton flipping between $S_z = \pm 1$, $\tau_e$ and $\tau_h$ are electron and hole spin flip times, and $\tau_r$ is the exciton recombination time (for the typical case when the energy splitting between $S_z = \pm 1$ and $S_z = \pm 2$ states due to the electron-hole exchange interaction is smaller than $k_B T$).

In GaAs single QW, $\tau_h$ and $\tau_{ex}$ are typically short, in the range of several tens of ps, while $\tau_r$ can reach tens and hundreds of ns in high-quality samples. It is the long electron spin relaxation time, which makes possible the spin transport of electrons over large distances, see [3, 8, 9, 10, 11]. For $\tau_{ex} \gg \tau_h, \tau_{ex}$, which is typical of GaAs single QW, $\tau_p \approx \tau_{ex}$ and, therefore, the small $\tau_{ex}$ results in a fast depolarization of the exciton emission within tens of ps [13, 14]. However, $\tau_{ex}$ is determined by the strength of the exchange Coulomb interaction between the electron and hole and is inversely proportional to the electron-hole overlap. This gives an opportunity to control the depolarization rate by changing the electron-
where \( F \) served at an energy below the hh direct exciton by (PLE) spectrum and polarization-resolved photoluminescence measured using a spectrometer with resolution 0.3 meV. The spatial resolution was 1.4 micron. The spectra were \( \tau_\text{ex} \) of magnitude longer than \( \sigma_\text{ex} \). The emission images in Fig. 1b were taken by a CCD with an interference filter 800 ± 5 nm, exciton recombination time \( \tau_\text{ex} \) of the indirect exciton. However, a substantial polarization of PL of indirect excitons was observed when the excitation was close to the hh direct exciton (Fig. 2b) at low temperatures (Fig. 2c). The polarization is reduced when the lh exciton (with \( m_h = \pm 1/2 \)) is excited (Fig. 2a), consistent with the data in Ref. [28] and related to increased spin phase space (e.g., for the exciton with \( s_z = \pm 1/2 \) and \( m_h = \pm 1/2 \) the hole spin relaxation \( m_h = +1/2 \rightarrow m_h = -3/2 \) changes the emission polarization from \( \sigma^+ \) to \( \sigma^- \)).

The measured degree of the circular polarization \( P \) (Fig. 2c) and the measured exciton lifetime \( \tau_\text{ex} \) [20] give an opportunity for estimating the polarization relaxation time \( \tau_\text{p} \) using the rate equations [13, 14], which result to \( \tau_\text{p} = \tau_\text{ex} P/(1 - P) \). The estimate for \( \tau_\text{p} \) is presented in the inset to Fig. 2c (the dependence of \( \tau_\text{ex} \) on parameters, such as temperature in Fig. 2 and excitation power in Fig. 4, is taken into account in the estimates). The depolarization time of the emission of indirect excitons reaches 10 ns (Fig. 2c), orders of magnitude higher than that of the direct excitons in single QW [13, 14]. The depolarization time of the emission of indirect excitons \( \tau_\text{p} \) is comparable to the exciton transport over large distances, which can reach tens and hundreds of microns [21, 22, 23, 24, 25, 26].

We probed exciton spin transport in a GaAs/AlGaAs CQW structure. Two 8 nm GaAs QW were separated by a 4 nm Al\(_{0.33}\)Ga\(_{0.67}\)As barrier and surrounded by 200 nm Al\(_{0.33}\)Ga\(_{0.67}\)As layers (see sample details in [20] where the same sample was studied). The electric field across the sample was controlled by an applied gate voltage \( V_g \). The excitons were photoexcited by a cw 633 nm HeNe laser or tunable Ti:Sapphire laser focused to a spot ∼ 5 µm in diameter. The excitation was circularly polarized (\( \sigma^+ \)). The emission images in \( \sigma^+ \) and \( \sigma^- \) polarizations were taken by a CCD with an interference filter 800 ± 5 nm, which covers the spectral range of the indirect excitons. The spatial resolution was 1.4 micron. The spectra were measured using a spectrometer with resolution 0.3 meV.

Figure 2a shows the photoluminescence excitation (PLE) spectrum and polarization-resolved photoluminescence (PL) spectra of the indirect excitons. PLE reveals two peaks in the exciton absorption which correspond to the heavy-hole (hh) and light-hole (lh) direct excitons. The emission of the hh indirect exciton is observed at an energy below the hh direct exciton by ∼ \( eF_zd \), where \( F_z \) is the electric field and \( d \) is the distance between the electron and hole layers in CQW (corrections due to the interaction are described in [27]). Figure 2b shows degree of the circular polarization of PL of indirect excitons. No polarization was observed at strongly nonresonant excitation by HeNe laser ∼ 400 meV above the indirect exciton. However, a substantial polarization of PL of indirect excitons was observed when the excitation was close to the hh direct exciton (Fig. 2b) at low temperatures (Fig. 2c). The polarization is reduced when the lh exciton (with \( m_h = \pm 1/2 \)) is excited (Fig. 2a), consistent with the data in Ref. [28] and related to increased spin phase space (e.g., for the exciton with \( s_z = \pm 1/2 \) and \( m_h = \pm 1/2 \) the hole spin relaxation \( m_h = +1/2 \rightarrow m_h = -3/2 \) changes the emission polarization from \( \sigma^+ \) to \( \sigma^- \)).

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a function of $r$ by dotted lines. (f) PL intensity of indirect excitons in $\sigma$ density at $P^2$ is described in the text.

FIG. 3: (a) Energy-$x$ images of the PL intensity of indirect excitons in $\sigma^+$ and $\sigma^-$ polarizations; $V_g = -1.1$ V, $E_{ex} = 1.572$ eV, $P_{ex} = 140\mu W$, $x - y$ images of the PL intensity of indirect excitons in $\sigma^+$ and $\sigma^-$ polarizations for (b) $P_{ex} = 15\mu W$ and (c) $P_{ex} = 4.7\mu W$; $V_g = -1.1$ V, $E_{ex} = 1.582$ eV. (d) PL spectra of indirect excitons at the center of the exciton cloud ($r = 0$) in $\sigma^+$ (red) and $\sigma^-$ (black) polarizations. The estimated exciton density at $r = 0$ for $P_{ex} = 2.3\mu W$, $45\mu W$, and $230\mu W$ is $9 \times 10^9$, $2 \times 10^{10}$, and $4 \times 10^{10}$ cm$^{-2}$, respectively. The density estimation is described in the text. $E_{ex} = 1.572$ eV. (e) PL polarization as a function of $r$ for the same $P_{ex}$ as in (d). The profile of the bulk emission, which presents the excitation profile, is shown by dotted lines. (f) PL intensity of indirect excitons in $\sigma^+$ (red) and $\sigma^-$ (black) polarizations as a function of $r$ for the same $P_{ex}$ as in (d,e). $T_{bulk} = 1.7$ K.

to their lifetime $\tau_r$, which is in the range of tens of ns [20].

Characteristic polarization-resolved energy-$x$ and $x-y$ images are shown in Fig. 3a-c. Figure 3d shows the density dependence of the spectra of the indirect excitons at the center of the exciton cloud in $\sigma^+$ and $\sigma^-$ polarizations. The polarization and estimate for the polarization relaxation time is shown in Figs. 4a,b. The exciton density $n$ was estimated from the energy shift $\delta E$ as $n = \epsilon_0 \epsilon_0 / 4\pi e^2 d$ [25] (note that a higher estimate for $n$ was suggested in Ref. 29). The polarization degree of the exciton emission (Figs. 3d, 4a) and the polarization relaxation time (Fig. 4b) reduce with increasing density. (Note that no increase of $P$ with $n$ such as reported in Ref. [22] was observed in the present experiments.) Note also that this density dependence is consistent with the observed reduction of polarization when the excitation energy corresponds to hh exciton, 1.572 eV, where an increased absorption results in a high density (Fig. 1b).

The increase of applied gate voltage $|V_g|$ results in the reduction of the electron-hole overlap and, in turn, increase of both $\tau_r$ and $\tau_{\text{ex}}$. The former was measured in Ref. [20] for the sample. The polarization $P = \tau_p/\tau_e$ reduces with reducing electron-hole overlap (i.e. at higher $|V_g|$), see the data for $V_g = -1.1$ and $-1.6$ V in Fig. 4a. Such dependence indicates a slower increase of $\tau_p$ than $\tau_r$ with increasing $|V_g|$. This is consistent with the saturation of $\tau_p$ in the limit of vanishing electron-hole overlap where $\tau_{\text{ex}}$ becomes large compared to $\tau_r$ and $\tau_{\text{h}}$ so that $\tau_p^{-1} = 2(\tau_r + \tau_{\text{h}})^{-1} + \tau_{\text{ex}}^{-1}$ is determined by $\tau_{\text{ex}}$, for which no substantial dependence on the electron-hole overlap is expected [13, 14]. (This is also consistent with the fact that essentially no polarization of the emission of the indirect excitons was observed in another studied GaAs/AlGaAs CQW sample with 15 nm QWs; in this sample, the larger separation between the electron and hole layers results to a much smaller electron-hole overlap, as revealed by a considerably longer $\tau_{\text{ex}}$ in the range of several $\mu s$.) Figure 4b indicates that $\tau_p = \tau_r P/(1 - P)$ still increases with reducing electron-hole overlap (i.e. at higher $|V_g|$).

The radius of the exciton cloud is essentially equal to the excitation spot radius at low densities and increases at high densities, Figs. 3b, c, f, 4c. Such behavior was observed earlier and attributed to the exciton localization due to in-plane disorder at low densities and exciton de-localization and transport away from the excitation spot.
that in the case of electron transport, the spin Coulomb
energy exceeds that of regular direct excitons by orders of mag-
nitude and reaches ten ns. The polarization degree and
the polarization relaxation time reduce with increasing
density and temperature. Spin transport of the indirect
excitons was observed. The exciton spin transport or-
ginates from the long spin relaxation time and long lifetime
of the indirect excitons.

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