Quasi two-dimensional carriers in dilute-magnetic-semiconductor quantum wells under in-plane magnetic field

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Abstract

Due to the competition between spatial and magnetic confinement, the density of states of a quasi two-dimensional system deviates from the ideal step-like form both quantitatively and qualitatively. We study how this affects the spin-subband populations and the spin-polarization as functions of the temperature, $T$, and the in-plane magnetic field, $B$, for narrow to wide dilute-magnetic-semiconductor quantum wells. We focus on the quantum well width, the magnitude of the spin-spin exchange interaction, and the sheet carrier concentration dependence. We look for ranges where the system is completely spin-polarized. Increasing $T$, the carrier spin-splitting, $U_{\sigma\sigma}$, decreases, while increasing $B$, $U_{\sigma\sigma}$ increases. Moreover, due to the density of states modification, all energetically higher subbands become gradually depopulated.

\textit{Key words:} spintronics, dilute magnetic semiconductors, density of states, spin-polarization

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1 Introduction

The progress in understanding of transition-metal-doped semiconductors has been impressive \cite{123}. New phenomena and applications have been discovered, in transition metal doped III-V or II-VI compounds including quasi two-dimensional systems \cite{45} where wave function engineering may play a substantial role e.g. increase the ferromagnetic transition temperature.

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An in-plane magnetic field distorts the density of states (DOS) \cite{6,7} of a quasi two-dimensional system because the spatial and the magnetic confinement compete. The energy dispersion in the \textit{xz}-plane has the form \( E_{i,\sigma}(k_x) \), where \( i \) is the subband index, \( \sigma \) is the spin, \( k_x \) the in-plane wave vector perpendicular to the in-plane magnetic field, \( B \) (applied along \( y \)), and \( z \) is the growth axis. The envelope functions along \( z \) depend on \( k_x \) i.e., \( \psi_{i,\sigma,k_x}(r) \propto \phi_{i,\sigma,k_x}(z)e^{ik_xx}e^{ik_yy} \). This modification has been realized in transport \cite{8} and photoluminescence \cite{9} studies, as well as in the detection of plasmons in QWs \cite{10}. A fluctuation of the magnetization in dilute-magnetic-semiconductor (DMS) structures in cases of strong competition between spatial and magnetic confinement has been predicted at low enough temperatures \cite{11} and a compact DOS formula holding for any type of interplay between spatial and magnetic confinement exists \cite{11}:

\begin{equation}
\rho(\mathcal{E}) = \frac{A\sqrt{2m^*}}{4\pi^2\hbar} \sum_{i,\sigma} \int_{-\infty}^{+\infty} dk_x \frac{\Theta(\mathcal{E} - E_{i,\sigma}(k_x))}{\sqrt{\mathcal{E} - E_{i,\sigma}(k_x)}}, \tag{1}
\end{equation}

\( \Theta \) is the step function, \( A \) is the \( xy \) area of the structure, \( m^* \) is the effective mass. Generally, \( E_{i,\sigma}(k_x) \) must be self-consistently calculated \cite{7,8,9,11}. The \( k_x \)-dependence in Eq. \cite{11} increases the numerical cost by a factor of \( 10^2 - 10^3 \) in many cases. For this reason, in the past, the \( k_x \)-dependence has been quite often ignored, although this is only justified for narrow QWs. With the existing computational power, such a compromise is not any more necessary. In the limit \( B \to 0 \), the DOS retains the occasionally stereotypic staircase shape with the \textit{ideal} step \( \frac{1}{2}\frac{2mA^2}{\pi\hbar^2} \) for each spin. The DOS modification significantly affects the physical properties and specifically the spin-subband populations and spin polarization in DMS quantum wells (QWs) \cite{4}. For completeness, we notice that Eq. \cite{11} ignores disorder which -with the current epitaxial techniques- is important when the concentration of paramagnetic ions (e.g. Mn\textsuperscript{+2}) is high.

Here we briefly describe how the above mentioned DOS determines the spin-subband populations and the spin-polarization as functions of \( B \) and the temperature, \( T \), for DMS single QWs giving a few examples. Calculations for double QWs will hopefully be published in the future. For narrow QWs, it has been shown \cite{11} that the DOS is an almost “perfect staircase” with steps increasing only a few percent relatively to the ideal 2DEG step. In such a case, at very low \( T \), a completely spin-polarized system can also be achieved \cite{11}. 
U_{oo} = \frac{g^* m^*}{2m_e} \hbar \omega_c - y N_0 J_{sp-d} S B_S(\xi) = \alpha + \beta. \quad (2)

is the electron spin-splitting. $\hbar \omega_c$ is the cyclotron gap, $\alpha = \alpha(B)$ describes the Zeeman coupling between the spin of the itinerant carrier and the magnetic field, while $\beta = \beta(B, T)$ expresses the exchange interaction between the spins of the Mn\(^{+2}\) cations and the spin of the itinerant carrier. $g^*$ is the $g$-factor of the itinerant carrier. $y$ is the molecular fraction of Mn. $N_0$ is the concentration of cations. $J_{sp-d}$ is the coupling strength due to the spin-spin exchange interaction between the d electrons of the Mn\(^{+2}\) cations and the s- or p-band electrons, and it is negative for conduction band electrons. The factor $S B_S(\xi)$ represents the spin polarization of the Mn\(^{+2}\) cations. The spin of the Mn\(^{+2}\) cation is $S = 5/2$. $B_S(\xi)$ is the standard Brillouin function. Such a simplified Brillouin-function approach is quite common when dealing with quasi two-dimensional systems. This way, the spin-orbit coupling is not taken into account. This is certainly a simplification, since increasing $T$, the magnetization of the magnetic ions competes with spin-orbit coupling.

$$\xi = \frac{g_{Mn} \mu_B S B - J_{sp-d} S n_{down} - n_{up}}{k_B T}. \quad (3)$$

$k_B$ is the Boltzmann constant. $\mu_B$ is the Bohr magneton. $g_{Mn}$ is the $g$ factor of Mn. $n_{down}$ and $n_{up}$ are the spin-down and spin-up concentrations measured e.g. in cm\(^{-3}\), while $N_{s,down}$ and $N_{s,up}$ used below are the spin-down and spin-up two-dimensional (sheet) concentrations measured e.g. in cm\(^{-2}\). In Eq. 3 (and only there) we approximate $n_{down} - n_{up} \approx (N_{s,down} - N_{s,up})/L$, where $L$ is the QW width. The first term in the numerator of Eq. 3 represents the contribution of the Zeeman coupling between the localized spin and the magnetic field. The second term in the numerator of Eq. 3 (sometimes called “feedback mechanism”) represents the kinetic exchange contribution which -in principle- can induce spontaneous spin-polarization i.e. in the absence of an external magnetic field. Notice that $n_{down} - n_{up}$ is positive for conduction band electrons. Finally, for conduction band electrons, the spin polarization is

$$\zeta = \frac{N_{s,down} - N_{s,up}}{N_s}. \quad (4)$$

$N_s = N_{s,down} + N_{s,up}$ is the free carrier two-dimensional (sheet) concentration.

$B$ and $T$ influence the spin polarization in an opposite manner. Moreover, for each type of spin population, the in-plane magnetic field -via the distortion
of the DOS redistributes the electrons between the subbands i.e., all excited states become gradually depopulated \cite{4}. Thus, the spin polarization can be tuned by varying the temperature and the magnetic field.

3 A few results and some discussion

Details on the material parameters used here can be found elsewhere \cite{4}. Figure 1 depicts the spin polarization tuned by varying the parallel magnetic field and the temperature, for different choices of the well width. \(-J_{sp-d} = 12 \times 10^{-3} \text{ eV nm}^3\), while \(N_s = 1.566 \times 10^{11} \text{ cm}^{-2}\). Because of the DOS modification \cite{11}, resulting in different distribution of electrons among the spin-subbands \cite{4}, we witness a clear increase of \(\zeta = \zeta(L)\), i.e. \(\zeta(L = 60 \text{ nm}) > \zeta(L = 30 \text{ nm}) > \zeta(L = 10 \text{ nm})\). For \(B = 0\), \(\zeta\) vanishes, i.e. there is no spontaneous spin polarization phase due to the tiny “feedback mechanism” for this choice of material parameters. Detailed illustrations of the effect of an in-plane magnetic field on the energy dispersion as well as on the density of states, for different well widths, can be found elsewhere \cite{11,12}.

\[\begin{align*}
\text{Fig. 1. The spin polarization, } \zeta, \text{ tuned by varying: (a) the in-plane magnetic field, } B (T = 20 \text{ K}), \text{ and (b) the temperature, } T (B = 10 \text{ T}), \text{ for different well widths, } L = 10 \text{ nm, 30 nm, and 60 nm. } -J_{sp-d} = 12 \times 10^{-3} \text{ eV nm}^3.
\end{align*}\]

The influence of \(N_s\) on the spin-subband populations and the spin polarization for different values of the magnitude of the spin-spin exchange interaction, \(J\) is examined below. In a heterostructure with higher \(N_s\) we may require smaller values of \(J\) in order to completely spin-polarize carriers. Modifying \(J\), we have explored the \(N_s\) influence. For \(J = 12 \times 10^{-2} \text{ eV nm}^3\) there is a very small influence of \(N_s\) on \(\zeta\). The situation changes using \(J = 12 \times 10^{-1} \text{ eV nm}^3\). Figure 2 shows \(N_{ij}\) and \(\zeta\) tuned by varying \(N_s\) for \(L = 60 \text{ nm}, T = 20 \text{ K}\) and \(B = 0.01 \text{ T}\), using \(J = 12 \times 10^{-1} \text{ eV nm}^3\). The pair \(ij\) is defined in the following manner: 00 symbolizes the ground-state spin-down-subband, 10 the 1st excited spin-down-subband, 01 the ground-state spin-up-subband, and finally 11 symbolizes the 1st excited spin-up-subband. Increase of \(N_s\) from \(\approx\)
Fig. 2. The spin-subband populations, $N_{ij}$ and the spin polarization, $\zeta$ (full symbols), tuned by varying the sheet carrier concentration, $N_s$, for $L = 60$ nm, $T = 20$ K and $B = 0.01$ T, using $J = 12 \times 10^{-1}$ eV nm$^3$. The arrows indicate $N_s$ values where we compare with $B = 0.0001$ T in the text.

$1.0 \times 10^9$ cm$^{-2}$ to $\approx 1.0 \times 10^{11}$ cm$^{-2}$ is sufficient to completely spin-polarize carriers. This is purely due to the “feedback mechanism” stemming from the difference between the populations of spin-down and spin-up carriers. If we decrease $B$ from 0.01 T to 0.0001 T, then e.g. (a) for $N_s = 1.175 \times 10^9$ cm$^{-2}$, $\zeta$ changes from 0.497 to 0.005, (b) for $N_s = 3.917 \times 10^{10}$ cm$^{-2}$, $\zeta$ changes from 0.973 to 0.909, however, (c) for $N_s = 1.175 \times 10^{11}$ cm$^{-2}$, $\zeta$ remains 1. $N_{ij}$ and $\zeta$, as a function of $J$ are depicted in Fig. 3 $T = 20$ K, $B = 0.01$ T, $L = 60$ nm, $N_s = 2.349 \times 10^{11}$ cm$^{-2}$. Due to the small values of $B$, $N_{10} \approx N_{00}$ and $N_{11} \approx N_{01}$.

4 Conclusion

We have studied the spin-subband-populations and the spin-polarization of quasi two-dimensional carriers in dilute-magnetic-semiconductor single quantum wells under the influence of an in-plane magnetic field. The proper density of states was used for the first time, incorporating the dependence on the in-plane wave vector perpendicular to the in-plane magnetic field. We have examined a range of parameters, focusing on the quantum well width, the magnitude of the spin-spin exchange interaction, and the sheet carrier concentration. We have shown that varying these parameters we can manipulate the spin-polarization, inducing spontaneous (i.e. for $B \rightarrow 0$) spin-polarization.
Fig. 3. The spin-subband populations, $N_{ij}$ and the spin polarization, $\zeta$ (full symbols), as a function of $J$. $T = 20$ K, $B = 0.01$ T, $L = 60$ nm, $N_s = 2.349 \times 10^{11}$ cm$^{-2}$.

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