Spin dephasing in $n$-typed GaAs quantum wells in the presence of high magnetic fields in Voigt configuration

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We perform a many-body study of the spin dephasing due to the D’yakonov-Perel’ effect in $n$-typed GaAs (100) quantum wells under high magnetic fields in the Voigt configuration by constructing and numerically solving the kinetic Bloch equations. We include all the spin conserving scattering such as electron-phonon, the electron-nonnagnetic impurity as well as the electron-electron Coulomb scattering in our theory and investigate how the spin dephasing time (SDT) is affected by the initial spin polarization, impurity, and magnetic field. The dephasing obtained from our theory contains not only that due to the effective spin-flipping scattering first proposed by D’yakonov and Perel’ [Zh. Eksp. Teor. Fiz. 60, 1954 (1971)|Sov. Phys.-JETP 38, 1053 (1971)], but also the recently proposed many-body dephasing due to the inhomogeneous broadening provided by the DP term [Wu, J. Supercond.:Incorp. Novel Mechanism 14, 245 (2001); Wu and Ning, Eur. Phys. J. B 18, 373 (2000)]. We are able to investigate the spin dephasing with extra large spin polarization (up to 100 %) which has not been discussed both theoretically and experimentally. A huge anomalous resonance of the SDT for large spin polarizations is predicted under the high magnetic field we used.

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I. INTRODUCTION

The resent development of ultrafast nonlinear optical experiments$^{1,2,3,4,5,6,7,8,9,10,11,12,13,14}$ has stimulated immense interest in spintronics in semiconductors as it shows great potential of using the spin degree of freedom of electrons in place of/in addition to the charge degree of freedom for device application such as qubits, quantum memory devices, and spin transistors. In order to make use of the spin degree of freedom in semiconductor spintronics, it is crucial to have a thorough understanding of spin dephasing mechanism.

Three spin dephasing mechanisms have been proposed in semiconductors:$^{15,16}$ the Eliot-Yafet (EY) mechanism,$^{17,18}$ the D’yakonov-Perel’ (DP) mechanism,$^{19}$ and the Bir-Aronov-Pikus (BAP) mechanism.$^{20}$ In the EY mechanism, the spin-orbit interaction leads to mixing of wave functions of opposite spins. This mixing results in a nonzero electron spin flip due to impurity and phonon scattering. The DP mechanism is due to the spin-orbit interaction in crystals without inversion center, which results in spin state splitting of the conduction band at $k \neq 0$. This is equivalent to an effective magnetic field acting on the spin, with its magnitude and orientation depending on $k$. Finally, the BAP mechanism is originated from the mixing of heavy hole and light hole bands induces by spin-orbit coupling. Spin-flip (SF) scattering of electrons by holes due to the Coulomb interaction is therefore permitted, which gives rise to spin dephasing. The dephasing rates of these mechanisms for low polarized system are calculated in the framework of single particle approximation.$^{15}$ For GaAs, the EY mechanism is less effective under most conditions, due to the large band gap and low scattering rate for high quality samples. The BAP mechanism is important for either $p$-doped or insulating GaAs. For $n$-doped samples, however, as holes are rapidly recombined with electrons due to the presence of a large number of electrons, spin dephasing due to the regular BAP mechanism is blocked. Therefore, the DP mechanism (or possibly the EY mechanism under certain conditions) is the main mechanism of spin dephasing for $n$-type GaAs.

All the above mentioned spin dephasing mechanisms are either due to the SF scattering or treated as effective SF scattering. In additional to these spin dephasing mechanisms, three years ago Wu proposed a many-body spin dephasing mechanism which is due to the inhomogeneous broadening, such as energy dependence of $g$-factor$^{21,22}$ and/or the momentum $k$-dependence of the DP term.$^{22,23,24}$ Together with the SC scattering$^{21,22,23,24,25}$ Differing from the earlier study of the spin dephasing which comes from the SF scattering, the spin dephasing through inhomogeneous broadening is caused by irreversibly disrupting the phases between spin dipoles and is therefore a many-body effect.$^{22,23,25}$ This many-body spin dephasing mechanism has long been overlooked in the literature. Recently, we further showed that this inhomogeneous broadening effect also plays an important role in the spin transport.$^{26,27}$ Very recently, Bronold et al. also discussed the spin dephasing due to the $k$-dependence of the $g$ factor.$^{28}$

In our recent work Ref. 29, we have performed a many-body study of the spin dephasing due to the D’yakonov-Perel’ effect in $n$-typed GaAs (100) quantum wells for high temperatures ($\geq 120$ K) under moderate magnetic fields in the Voigt configuration by constructing and numerically solving the kinetic Bloch equations set up by Wu et al.$^{21,22,23,24,25,30}$ We include all the spin conserving scattering such as the electron-phonon, the electron-
nonmagnetic impurity as well as the electron-electron Coulomb scattering in our theory and investigate how the spin dephasing rate is affected by the initial spin polarization, temperature, impurity, magnetic field as well as the electron density. The dephasing obtained from our theory contains not only that due to the effective SF scattering first proposed by D'yakonov and Perel', but also the many-body dephasing due to the inhomogeneous broadening provided by the DP term. We show that for the electron densities we study, the spin dephasing rate is dominated by the many-body effect. Equally remarkable is that we are now able to investigate the spin dephasing with extra large spin polarization (up to 100 %) which has not been discussed both theoretically and experimentally. We find a dramatic decrease of the spin dephasing rate for large spin polarizations. The spin dephasing time (SDT), which is defined as the inverse of the spin dephasing rate, we get at low initial spin polarization is in agreement with the experiment both qualitatively and quantitatively.

In this paper, we further extend the above mentioned work to the case of the high magnetic fields \( B \geq 60 \text{ T} \). These high fields can be achieved experimentally by the pulsed magnetic field with the stable duration of the field pulse being milliseconds, orders of magnitude longer than the SDT.\(^{31,32} \) We will show a huge anomalous resonance of the SDT for large spin polarizations under this high magnetic field case. We organize the paper as follows: We briefly present our model and the kinetic equations in Sec. II. Then in Sec. III(A) we investigate how the SDT changes with the variation of the initial spin polarization. In Sec. III(B) we show the magnetic field dependence of the SDT. We present the conclusion and summary in Sec. IV.

II. KINETIC EQUATIONS

We start our investigation from an \( n \)-doped (100) GaAs QW with well width \( a \). The growth direction is assumed to be \( z \)-axis. A magnetic field \( B \) is applied along the \( x \) axis. Due to the confinement of the QW, the momentum states along \( z \) axis are quantized. Therefore the electron states are characterized by a subband index \( n \) and a two dimensional wave vector \( \mathbf{k} = (k_x, k_y) \) together with a spin index \( \sigma \). In the present paper, the subband separation is assumed to be large enough so that only the lowest subband is populated and the transition to the upper subbands is unimportant. Therefore, one only needs to consider the lowest subband. For \( n \)-doped samples, spin dephasing mainly comes from the DP mechanism.\(^{19} \) With the DP term included, the Hamiltonian of the electrons in the QW takes the form:

\[
H = \sum_{k\sigma \sigma'} \left\{ \epsilon_k + \left[ g_e B + \mathbf{h}(\mathbf{k}) \right] \cdot \mathbf{\sigma}_{\sigma \sigma'} \right\} c_{k\sigma}^\dagger c_{k\sigma'} + H_I. \tag{1}
\]

Here \( \epsilon_k = k^2/2m^* \) is the energy of electron with wavevector \( \mathbf{k} \) and effective mass \( m^* \). \( \mathbf{\sigma} \) are the Pauli matrices. In QW system, the DP term is composed of the Dresselhaus term\(^{33} \) and the Rashba term.\(^{34,35} \) The Dresselhaus term is due to the lack of inversion symmetry in the zincblende crystal Brillouin zone and is sometimes referred to as bulk inversion asymmetry (BIA) term. For the (100) GaAs QW system, it can be written as\(^{36,37} \)

\[
\begin{align*}
\hat{h}_x ^{\text{BIA}} (\mathbf{k}) &= \gamma k_x (k_y^2 - \langle k_z^2 \rangle) , \\
\hat{h}_y ^{\text{BIA}} (\mathbf{k}) &= \gamma k_y (\langle k_z^2 \rangle - k_x^2) , \\
\hat{h}_z ^{\text{BIA}} (\mathbf{k}) &= 0 . \tag{2}
\end{align*}
\]

Here \( \langle k_z^2 \rangle \) represents the average of the operator \(- (\mathbf{\sigma} \cdot \mathbf{\mathbf{r}})^2\) over the electronic state of the lowest subband and is therefore \((\pi/\alpha)^2\). \( \gamma = (4/3)(m^*/m_{cv})(1/\sqrt{2m^*E_g}(\eta/\sqrt{1 - \eta/3}) \) and \( \eta = \Delta/(E_g + \Delta) \), in which \( E_g \) denotes the band gap; \( \Delta \) represents the spin-orbit splitting of the valence band; \( m^* \) standing for the electron mass in GaAs; and \( m_{cv} \) is a constant close in magnitude to free electron mass \( m_0 \).\(^{16} \) Whereas the Rashba term appears if the self-consistent potential within a QW is asymmetric along the growth direction and is therefore referred to as structure inversion asymmetry (SIA) contribution. Its scale is proportional to the interface electric field along the growth direction. For narrow band-gap semiconductors such as InAs, the Rashba term is the main spin-dephasing mechanism; whereas in the wide band-gap semiconductors such as GaAs, the Dresselhaus term is dominant. In the present paper, we will take only the Dresselhaus term into consideration as we focus on the spin dephasing in GaAs QW. The interaction Hamiltonian \( H_I \) is composed of Coulomb interaction \( H_{ee} \), electron-phonon interaction \( H_{eh} \), as well as electron-impurity scattering \( H_I \). Their expressions can be found in textbooks.\(^{38,39} \)

We construct the kinetic Bloch equations by the nonequilibrium Green function method\(^{36} \) as follows:

\[
\hat{\rho}_{k,\sigma \sigma'} = \hat{\rho}_{k,\sigma \sigma'}|_{\text{coh}} + \hat{\rho}_{k,\sigma \sigma'}|_{\text{scatt}} \tag{3}
\]

Here \( \hat{\rho}_{k} \) represents the single particle density matrix. The diagonal elements describe the electron distribution functions \( \rho_{k,\sigma} = f_{k \sigma} \). The off-diagonal elements \( \rho_{k,\downarrow \uparrow} \equiv \rho_{k} \) describe the inter-spin-band polarizations (coherence) of the spin coherence.\(^{30} \) Note that \( \rho_{k,\downarrow \uparrow} \equiv \rho_{k,\uparrow \downarrow} \equiv \rho_{k} \). Therefore, \( f_{k \uparrow \downarrow} \) and \( \rho_{k} \) are the quantities to be determined from Bloch equations.

The coherent parts of the equation of motion for the electron distribution function and spin coherence are given by
respectively, where \( V_q = 4\pi e^2/|\kappa_0(q + q_0)| \) is the 2D Coulomb matrix element under static screening. \( q_0 = (e^2 m^*/\kappa_0) \sum_{k} f_{k,\sigma} \) and \( \kappa_0 \) is the static dielectric constant. The first term on the right hand side (RHS) of Eq. (4) describes spin precession of electrons under the magnetic field \( \mathbf{B} \) as well as the effective magnetic field \( \mathbf{h}(\mathbf{k}) \) due to the DP effect. The scattering terms \( \rho_{k,\sigma,\sigma'}|\text{scatt} \) contain the contribution of the electron-nonmagnetic impurity interaction and the electron-phonon coupling as well as the electron-electron Coulomb scattering. Their expressions can be found in our previous paper Ref. 29. The initial conditions are taken at \( t = 0 \) as:

\[
\rho_{k}|_{t=0} = 0 , \\
f_{k\sigma}|_{t=0} = 1 \left\{ \exp\left[ (\varepsilon_k - \mu_{\sigma})/k_B T \right] + 1 \right\} ,
\]

where \( \mu_{\sigma} \) is the chemical potential for spin \( \sigma \). The condition \( \mu_+ \neq \mu_- \) gives rise to the imbalance of the electron densities of the two spin bands. Eqs. (3) together with the initial conditions Eqs. (6) and (7) comprise the complete set of kinetic Bloch equations of our investigation.

### III. NUMERICAL RESULTS

The kinetic Bloch equations form a set of nonlinear equations. All the unknowns to be solved appear in the scattering terms. Specifically, the electron distribution function is no longer a Fermi distribution because of the existence of the anisotropic DP term \( \mathbf{h}(\mathbf{k}) \). This term in the coherent parts drives the electron distribution away from an isotropic Fermi distribution. The scattering term attempts to randomize electrons in \( \mathbf{k} \)-space. Obviously, both the coherent parts and the scattering terms have to be solved self-consistently to obtain the distribution function and the the spin coherence.

We numerically solve the kinetic Bloch equations in such a self-consistent fashion to study the spin precession between the spin-up and -down bands. We include electron-phonon scattering and the electron-electron interaction throughout our computation. As we concentrate on the relatively high temperature regime in the present study, for electron-phonon scattering we only need to include electron-LO phonon scattering. Electron-impurity scattering is sometimes excluded. As discussed in the previous paper, irreversible spin dephasing can be well defined by the slope of the envelope of the incoherently summed spin coherence \( \rho(t) = \sum_{k} |\rho_k| \). The material parameters of GaAs for our calculation are tabulated in Table I. The method of the numerical calculation has been laid out in detail in our previous papers. In the present calculation the total electron density \( N_e \) is chosen to be \( 4 \times 10^{11} \, \text{cm}^{-2} \) which is a typical electron density in the \( n \)-type GaAs QW’s. Differing from our previous paper where the applied magnetic field \( B \) is the moderate one, in this paper \( B \) is chosen to be 60 T unless otherwise specified. Although this large magnetic field maybe an impractical one in the device application, it is of theoretical interest to understand and study the spin dephasing in this extreme condition. Moreover, this study can also throw lights on the understanding of spin dephasing under a moderate magnetic field of other materials with large Landé \( g \)-factors such as InAs where \( g = 15 \).

| \( \kappa_{\infty} \) | 10.8 | \( \kappa_0 \) | 12.9 |
| \( \omega_0 \) | 35.4 meV | \( m^* \) | 0.067 \( m_0 \) |
| \( \Delta \) | 0.341 eV | \( E_g \) | 1.55 eV |
| \( g \) | 0.44 |

TABLE I: Parameters used in the numerical calculations

We have studied SDT under the high magnetic fields for all the situations as we did in Ref. 29. Many features such as the temperature dependence, electron density dependence as well as the contribution of the Coulomb scattering are similar to the results we got under moderate magnetic fields. In this paper, we just report the results with different properties. Our main results are plotted in Figs. 1 to 5.

In Fig. 1 we plot a typical temporal evolution of the spin signal in a GaAs QW at \( T = 200 \, \text{K} \) where the electron densities in the spin-up and -down bands together with the incoherently summed spin coherence are plotted versus time for \( N_i = 0 \). At \( t = 0 \), the initial spin polarization \( P = (N_{1/2} - N_{-1/2})/(N_{1/2} + N_{-1/2}) \) is 2.5%. It is seen from the figure that excess electrons in the spin-up band start to flip to the spin-down band at \( t = 0 \) due to the presence of the magnetic field and the DP term \( \mathbf{h}(\mathbf{k}) \). In the meantime the spin coherence \( \rho \) accumulates. At about 0.67 ps, the electron densities in the two spin bands become equal and the spin coherence reaches its maximum. Then the spin coherence starts to feed back...
and the electron density in the spin-down band exceeds that in the spin-up band while \( \rho \) decreases. At about 1.3 ps, \( \rho \) reach its minimum, while the density difference in the two spin bands reaches its maximum again with the excess electrons now in the spin-down band. Due to the dephasing, the second peak is lower than the first one. This oscillation goes on until the amplitude of the oscillation becomes zero due to the dephasing. In Fig. 1, we also plotted the slope of the envelope of the incoherently summed spin coherence as dashed line. From the slope one gets the spin dephasing time.

![Graph showing electron densities and spin dephasing time](image)

**FIG. 1**: Electron densities of up spin and down spin and the incoherently summed spin coherence \( \rho \) versus time \( t \) for a GaAs QW with the initial spin polarization \( P = 2.5\% \) at \( T = 200 \text{ K} \). The dashed line gives the envelope of \( \rho \). Note the scale of the spin coherence is on the right side of the figure.

**A. Spin polarization dependence of the spin dephasing time**

We first study the spin polarization dependence of the SDT. As our theory is a many-body one and we include all the scatterings, especially the Coulomb scattering, in our calculation, we are able to calculate the SDT with large spin polarization.

In Fig. 2, SDT \( \tau \) is plotted against the initial spin polarization \( P \) for GaAs QW's with \( N_i = 0 \) [Fig. 2(a)] and \( N_i = 0.1N_e \) [Fig. 2(b)] at different temperatures. Differing from the moderate magnetic field case where the SDT increases monotonically with the initial spin polarization,\(^{29}\) here the most striking feature of the impurity-free case is the huge anomalous peaks of the SDT in low temperatures. For \( T = 120 \text{ K} \), the peak value of the SDT is about 6 times higher than that of low initial spin polarization. It is also seen from the figure that the anomalous peak is reduced with the increase of temperature and the peak shifts to higher polarization. For \( T > 200 \text{ K} \) there is no anomalous peak.

The anomalous peak in the \( \tau-P \) curve in low temperature region originates from the electron-electron in-
FIG. 3: Spin dephasing time $\tau$ versus the initial spin polarization $P$ for a GaAs QW with different impurity levels. Circle (●): $N_i = 0$; Diamond (♦): $N_i = 0.01 N_e$; Square (■): $N_i = 0.1 N_e$. The lines are plotted for the aid of eyes.

interaction, specifically the Hartree-Fock (HF) self-energy [i.e., the last terms in the Eq. (4) and (5)]. If one removes the HF term, the anomalous peak as well as the large increase of SDT disappears. It is pointed out in our previous paper that although the HF term itself does not contribute to the spin dephasing directly, it can alert the motion of the electrons as it behaves as an effective magnetic field $B^{\text{HF}}(k)$. Therefore, the HF term can affect the spin dephasing by combining with the DP term. For small spin polarization as commonly discussed in the literature, the contribution of the HF term is marginal. However, when the polarization gets higher, the HF contribution becomes larger. Especially the effective magnetic field formed by the HF term contains a longitudinal component $\hat{B}^{\text{HF}}_z(k)$ which can effectively reduce the “detuning” of the spin-up and -down electrons, and thus strongly reduces the spin dephasing, therefore the SDT increases with initial spin polarization. Moreover, besides the initial polarization, $\rho_k$ and therefore $B^{\text{HF}}(k)$ are also affected by the applied magnetic field. With higher magnetic field, both gets larger. Under the high magnetic field and when the initial spin polarization reaches to a right value, the effective magnetic field $B^{\text{HF}}(k)$ may reach the magnitude comparable to the contribution from the DP term as well as the applied magnetic field in the coherent parts of the Bloch equations and reduces the anisotropic caused by the DP term. Therefore, one gets much longer SDT. However, if one further increases the initial polarization, the HF term exceeds the resonance condition. As the result, the SDT decreases. Therefore, one gets the anomalous peak which is similar to the resonance effect. It is noted at, as both the DP term and the HF term are $k$-dependent, the resonance is broadened.

For high temperatures the HF term is smaller. In order to reach the resonance, one needs to go to higher polarization. Therefore, as shown in the figure the anomalous peak shifts to the higher polarization. However, when the temperature is high enough, even largest polarization $P = 100 \%$ cannot make the HF term to reach the resonance condition. Therefore, the peak disappears.

The $\tau$-$P$ curve is much different when the impurities are introduced. It is seen from Fig. 2(b) that, when the density of impurity is large, say $N_i = 0.1 N_e$, the fast rise in $\tau$-$P$ curve remains. Nevertheless the increase is much smaller than the corresponding one when the impurities are absent. In addition to the reduction of the rise in $\tau$-$P$ curves, the impurities destroy the anomaly too. One can easily see that, with the impurity level $N_i = 0.1 N_e$, for all of the temperatures we study, the SDT increases uniquely with the polarization.

To further reveal the contribution of the impurity to the dephasing under different conditions, we plot the SDT as a function of the polarization for different impurity levels at $T = 120 \text{ K}$ and $200 \text{ K}$ in Fig. 3(a) and (b) respectively. The figure clearly shows that for low temperature, the impurity tends to remove the anomalous peak and to shift the peak to the larger initial spin polarization. This is because that the impurity reduces the HF term and therefore the resonance effect is also reduced. Hence, in order to reach the maximum resonance, one has to increase the initial spin polarization. Consequently, the peak shifts to larger $P$. Whereas when $N_i$ is raised to $0.1 N_e$, the HF term is reduced too much to form a peak. It is also noted that for high temperatures, there is no anomalous peak.

It is interesting to note that in the low polarized regime
and when the temperature is 120 K, $\tau$ first decreases when the impurities are introduced. However, when we further increase the impurity level from $N_i = 0.01N_e$ to $N_i = 0.1N_e$, $\tau$ increases again. As we pointed out before that the impurities affect the spin dephasing in two ways. On one hand, the electron-impurity scattering provides a new spin dephasing channel through combining with the DP term to give an effective SF scattering and through the inhomogeneous broadening provided by the DP term. This gives rise to the enhancement of the dephasing. On the other hand, the scattering also redistributes the electrons in the momentum space and leads them to an isotropic distribution. Therefore, the scattering can suppress the anisotropy caused by the DP term, consequently the effective spin-flipping scattering. This leads to a smaller spin dephasing.

Our result indicates that in low temperature and low polarization region, the impurities tend to reduce the SDT through the added spin dephasing channel when their concentration is small. When the impurity level increases, the impurities destroy the anisotropy introduced by DP effect more effectively and the electron-impurity scattering leads to an increase in the SDT. This feature is different for high temperatures as shown in Fig. 2(b), where the SDT increases with the increase of the impurity density. The reason is understood as the reduction of the inhomogeneous broadening for high temperature (see more detail in our previous paper Ref. 29). Therefore, the second effect mentioned above dominants. Consequently, the scattering tends to reduce the dephasing and the dephasing time increases with the concentration of the impurities.

B. Magnetic field dependence of the spin dephasing

We now investigate the magnetic field dependence of the spin dephasing. In Fig. 4, we plot the SDT versus the applied magnetic field for different impurity levels and different spin polarizations. It is seen that for all the cases we study, the SDT increases with the magnetic field. This is because in the presence of a magnetic field, the electron spins undergo a Larmor precession around the magnetic field. This precession suppresses the precession about the effective magnetic field $h(k)$. Therefor the SDT increases with the magnetic field. It is pointed out that in 3D electron gas, the magnetic field also forces electrons to precess around it. This precession introduces additional symmetry in the momentum space that limits the k-space available to the DP effect which is anisotropic in it. This can further reduce the spin dephasing. However, it is expected that this effect in the 2D case is less effective than the 3D case as in z-direction the momentum is quantized and the momentum precession around the magnetic field should be suppressed.

In additional to the above mentioned effect of the magnetic field on spin dephasing, one can further see from Fig. 4, that for large polarization, the magnetic field also enhances the HF term. As we mentioned before, for large...
polarization, the contribution from the HF term is important. Increase of the HF term serves as additional magnetic field which further suppresses the effect of the DP term $\mathbf{h}(k)$, and therefore results in a faster rise in the $\tau-B$ curve. To reveal more concrete about the combining effect of the magnetic field and the HF term on spin dephasing, we plot the SDT as a function of polarization in Fig. 5. It is shown that the rise in the $\tau-P$ curve increases with the magnetic field. Moreover, the position of the peak in $\tau-P$ shifts to a larger polarization. This is understood that, it needs a larger HF term, and hence a larger spin polarization, to achieve the resonance condition when the magnetic field increases. When the magnetic field is raised to 8 T, it is no longer possible to form the resonance for all of the polarization. As a result the SDT increases uniquely with the polarization and there is no peak in the $\tau-P$ curve.

IV. CONCLUSION

In conclusion, we have performed a systematic investigation of the DP effect on the spin dephasing of $n$-typed GaAs QW’s under high magnetic fields in Voigt configuration. Based on the nonequilibrium Green’s function theory, we derived a set of kinetic Bloch equations for a two-spin-band model. This model includes the electron-phonon, electron-impurity scattering as well as the electron-electron interaction. By numerically solving the kinetic Bloch equations, we study the time evolution of electron densities in each spin band and the spin coherence—the correlation between spin-up and -down bands. The SDT is calculated from the slope of the envelope of the time evolution of the incoherently summed spin coherence. We therefore are able to study in detail how this dephasing time is affected by various factors such as spin polarization, temperature, impurity level, magnetic field and electron density. In this paper we focus ourselves on the special features of the SDT under high magnetic fields. Features which are similar to those in the moderate magnetic fields have been reported in our previous paper Ref. 29 and are therefore not repeated in this paper.

It is discovered that the SDT increases with the initial spin polarization. Moreover, for low impurity level and low temperature, there is a giant anomalous resonant peak in the curve of the SDT versus the initial spin polarization. This resonant peak moves to high spin polarization and its magnitude is fast reduced (enhanced) until the whole resonance disappears if one increases the impurity density and/or the temperature (the magnetic field). It is discovered that this anomalous resonance peak originates from the HF contribution of the electron-electron Coulomb interaction. Under the right spin polarization, the contribution of HF term may reach the magnitude comparable to the contribution of the DP term as well as the magnetic field in the coherent parts of the Bloch equations and reduces the anisotropy caused by the DP effect—consequently reduces the spin dephasing. As the resonance is the combined effects of the HF term, the DP term and the magnetic field, the magnitude and position of the resonance peak are affected by all the factors that can alert the magnitude of the HF term, such as temperature, impurity scattering, magnetic field as well as the electron density: For a given impurity concentration, when the temperature increases, the HF term reduces. Consequently the $\tau-P$ curve is smoothed and the peak position is moved to higher spin polarization; For impurities free samples, if the the temperature is raised to 200 K, the HF term is reduced too much to form a resonance and the anomalous peak disappears; The same situation happens when the impurity level increases at a given temperature as the scattering also lowers the HF term. When the impurity level is raised to 0.1 $N_e$ there is no resonance in the temperature region we studied. While the increase of the magnetic field enhances the HF term and results in a faster increase of the SDT as well as a higher resonant peak in $\tau-P$ curve. Moreover, as the magnetic field becomes larger, it needs a larger HF term and hence a larger polarization in order to achieve the resonant condition. Therefore the peak position is also moved to higher polarization. It is further noted that the resonance condition can only be achieved with high magnetic fields. For moderate magnetic fields, the contribution of the magnetic field is not big enough to reach the resonance condition for GaAs due to the small $g$ factor of this material.

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