Spin relaxation in \textit{n-type} (111) GaAs quantum wells

B. Y. Sun,\textsuperscript{1,2} P. Zhang,\textsuperscript{2} and M. W. Wu\textsuperscript{1,2,\textcopyright}  
\textsuperscript{1}Hefei National Laboratory for Physical Sciences at Microscale, University of Science and Technology of China, Hefei, Anhui, 230026, China  
\textsuperscript{2}Department of Physics, University of Science and Technology of China, Hefei, Anhui, 230026, China  
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We investigate the spin relaxation limited by the D'yakonov-Perel' mechanism in \textit{n-type} (111) GaAs quantum wells, by means of the kinetic spin Bloch equation approach. In (111) GaAs quantum wells, the in-plane effective magnetic field from the D'yakonov-Perel' term can be suppressed to zero on a special momentum circle under the proper gate voltage, by the cancellation between the Dresselhaus and Rashba spin-orbit coupling terms. When the spin-polarized electrons mainly distribute around this special circle, the in-plane inhomogeneous broadening is small and the spin relaxation can be suppressed, especially for that along the growth direction of quantum well. This cancellation effect may cause a peak (the cancellation peak) in the density or temperature dependence of the spin relaxation time. In the density (temperature) dependence, the interplay between the cancellation peak and the ordinary density (Coulomb) peak leads to rich features of the density (temperature) dependence of the spin relaxation time. The effect of impurities, with its different weights on the cancellation peak and the Coulomb peak in the temperature dependence of the spin relaxation, is revealed. We also show the anisotropy of the spin relaxation with respect to the spin-polarization direction.

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I. INTRODUCTION

In the past decades, great efforts have been devoted to the understanding of the spin relaxation in various systems, aiming to incorporate the spin degree of freedom of carriers into the traditional electronic devices.\textsuperscript{1–6} In \textit{n-type} III-V zinc-blende semiconductors, the spin relaxation is mainly governed by the D'yakonov-Perel' (DP) mechanism\textsuperscript{2} via the joint effects of the momentum scattering and the \textit{k}-dependent effective magnetic field (inhomogeneous broadening)\textsuperscript{2} induced by the DP spin-orbit coupling.\textsuperscript{2} The DP spin-orbit coupling is contributed by the Dresselhaus\textsuperscript{2} term as well as the possible Rashba\textsuperscript{2} term if the structure inversion symmetry is broken. In quantum-well structure, the effective magnetic field from the gate-voltage tunable Rashba term is proportional to \( \mathbf{k} \times \hat{z} \) (\( \hat{z} \) is the growth direction), whereas that from the Dresselhaus term varies with the growth direction. Therefore, with special growth direction, spin-polarization direction and/or relative strength of the Rashba and Dresselhaus terms, spin relaxation may show intriguing properties. In (001) asymmetric GaAs quantum wells, the relaxation for spins along [110] or [110] can be strongly suppressed when the Rashba and Dresselhaus terms are comparable in magnitude.\textsuperscript{11} In (110) symmetric GaAs quantum wells, the effective magnetic field solely contributed by the Dresselhaus term is along the growth direction.\textsuperscript{12} Therefore for spins along the growth direction the DP relaxation mechanism is absent.\textsuperscript{13–20} Other relaxation mechanisms should be taken into account.\textsuperscript{13–20}

For (111) III-V zinc-blende quantum wells, the spin relaxation may also show rich properties, due to the interplay of the Rashba and Dresselhaus terms. Setting the \( \hat{z} \)-axis along the growth direction \([111]\), \( \hat{x} \)-axis along \([110]\) and \( \hat{y} \)-axis along \([112]\), the DP term for the lowest subband can be expressed as

\[
\Omega_x(k) = \gamma(\frac{-k^2 + 4(k_x^2)}{2\sqrt{3}})k_y - \alpha E_z k_y, \quad (1)
\]

\[
\Omega_y(k) = -\gamma(\frac{-k^2 + 4(k_x^2)}{2\sqrt{3}})k_x + \alpha E_z k_x, \quad (2)
\]

\[
\Omega_z(k) = \frac{k_z^3 - 3k_x k_y^2}{\sqrt{6}}. \quad (3)
\]

 decrees contained coefficient \( \gamma (\alpha) \) are contributed by the Dresselhaus (Rashba) spin-orbit coupling; \( E_z \) stands for the electric field from the gate voltage and \( \langle k_x^2 \rangle_{00} = (\pi/a)^2 \) is the average of the operator \( -(\partial^2/\partial x^2) \) over the electron state of the lowest subband under the infinite-depth square well assumption. \( \Omega(k) \) is referred to as the effective magnetic field, while the spin-orbit coupling term in the Hamiltonian introduced by the DP mechanism is expressed as \( H_{so} = \Omega(k) \cdot \sigma /2 \). Based on Eqs. (1)-(3), Cartoixà \textit{et al.} proposed that a peak of the spin relaxation time (SRT) in the gate-voltage dependence appears at \( E_z \approx 4(k_{z,00}^2)/(2\sqrt{3}\alpha e) \) in (111) GaAs quantum wells when the cubic term in \( \Omega(k) \) is neglected.\textsuperscript{23} In (111) InGaAs quantum wells, Vurgaftman and Meyer also investigated the spin relaxation, showing that the temperature affects the gate-voltage dependence of the inhomogeneous broadening strongly and hence the SRT.\textsuperscript{22} Both investigations are based on the single-particle approach.

Besides the gate-voltage dependence, the electron density and temperature dependences of the SRT can also show special properties. For convenience, we rewrite the
in-plane DP term as

$$\Omega_{\perp}(k) = [(k^2 - 4(k_z^2)_{00})\gamma/2\sqrt{3} + \alpha e E_z]\vec{z} \times \vec{k}. \quad (4)$$

From this equation, one finds that when $k^2$ is equal to the critical value modulated by the gate voltage:

$$k_c^2 = 4(k_z^2)_{00} - 2\sqrt{3}\alpha e E_z/\gamma, \quad (5)$$

$\Omega_{\perp}(k)$ becomes zero as shown by the circle in the schematic of $\Omega(k)$ in Fig. 1. It is noted that this phenomenon only happens when $E_z < 4(k_z^2)_{00}\gamma/(2\sqrt{3}\alpha e)$, i.e., $k_c^2 > 0$. Under this condition, the SRT becomes zero as the in-plane components of the effective magnetic field are exactly zero on the critical circle in the limit of zero temperature. However, in reality, the temperature is higher than zero and the distribution of the spin-polarized electrons spreads out around the average Fermi momentum. Also, the electron density can be changed and hence the average Fermi momentum can be shifted away from $k_c$. Even so, with proper temperature and/or electron density, the condition $k^2 = k_c^2$ can be satisfied and then the in-plane inhomogeneous broadening ($\Omega_{\perp}^2(k)$) is suppressed. This may lead to the nonmonotonicity of the inhomogeneous broadening in the temperature or electron density dependence. In the following, we refer to this effect as the “cancellation effect” due to the cancellation between the Dresselhaus and Rashba terms. It is noted that the cancellation effect is more obvious at low temperature. It may also take place when considering spin relaxations along other directions. However, when the spin polarization is deviated from the $z$-axis, the cancellation effect becomes weaker as the inhomogeneous broadening from $\Omega_z(k)$ comes into play. The nonmonotonicity of the inhomogeneous broadening may lead to a peak of the SRT in the temperature or electron density dependence. We call this peak as the “cancellation peak”, which to our knowledge has not been studied in the literature and is hence the main focus of this work.

However, the scenario is not as simple as that presented above, since the spin relaxation is determined by the joint effects of the inhomogeneous broadening and the scattering. The scattering together with the inhomogeneous broadening further lead to a plenty of features in the electron density or temperature dependence of the SRT. In fact, as revealed in the previous works, the Coulomb scattering plays an important role in the spin relaxation.\textsuperscript{25,26,27} The nonmonotonic dependence of the Coulomb scattering rate $1/\tau_{ee}$ on temperature $T$ during the crossover of electrons from the degenerate to nondegenerate limits [e.g., for two-dimensional electrons $1/\tau_{ee} \propto T^2 (T^{-1})$ when $T < T_F$ ($T > T_F$) with $T_F$ denoting the Fermi temperature];\textsuperscript{29} can lead to a peak in the temperature dependence of the SRT in the strong scattering limit when the Coulomb scattering dominates.\textsuperscript{27,31} This peak is called as the “Coulomb peak” in the temperature dependence. It appears around $T_F$, with the location influenced by the temperature dependence of the inhomogeneous broadening and thus being sample dependent. The increase of the inhomogeneous broadening with increasing temperature tends to shift the peak towards a lower temperature. The peak was predicted to be close to $T_F$ in $n$-type bulk GaAs quantum wells;\textsuperscript{27} while later observed experimentally at about $T_F/2$ in $n$-type high-mobility (001) GaAs/Si quantum wells;\textsuperscript{30–35} In intrinsic bulk GaAs, this peak was predicted to be at about $T_F$ ($T_F/2$)\textsuperscript{28} In intrinsic bulk GaAs, this peak was predicted to be close to $T_F$ in $n$-type high-mobility (001) GaAs/GaAlAs heterostructure.\textsuperscript{29} In $p$-type high-mobility (001) Si/SiGe (Ge/SiGe) quantum wells, the peak was predicted to be at about $T_F$ ($T_F/2$)\textsuperscript{31} In intrinsic bulk GaAs, this peak was predicted to be at about $T_F$ ($T_F/2$)\textsuperscript{31} Nevertheless, when impurities are added, the Coulomb peak can be destroyed.\textsuperscript{27,30,31} For the carrier density dependence of the SRT, a peak also appears around the crossover of the nondegenerate and degenerate limits.\textsuperscript{27,31} This is because the inhomogeneous broadening varies little with density in the nondegenerate limit where the Boltzmann distribution can be well satisfied but increases with increasing density in the degenerate limit [this monotonic dependence widely exists in the systems where the cancellation effect is absent, such as (001) GaAs quantum wells or bulk GaAs]. Therefore, if the total scattering rate increases with increasing density in the nondegenerate limit, the SRT increases also provided the system is in the strong scattering limit. In the degenerate limit, the increase of the inhomogeneous broadening with increasing density is faster than that of the scattering, and thus the SRT decreases with the increase of density. Consequently a peak (the normal density peak) appears.\textsuperscript{27,31} It is noted that all the scatterings can contribute to this peak. Nevertheless, in the system where the Coulomb scattering dominates, this density peak is referred to as the Coulomb peak in the density dependence in this manuscript. Similar to the Coulomb peak in the temperature dependence, the location of the density peak is also sample dependent, usually with the corresponding Fermi temperature $T_F \sim T/2-T$;\textsuperscript{29,34–35} The above phenomena may also arise here.
in (111) GaAs quantum wells and lead to a distinguishable peak in the regime away from the cancellation peak. Moreover, when this peak and the cancellation peak appear simultaneously, they may even interplay with each other.

In this work, we adopt the fully microscopic many-body kinetic spin Bloch equation (KSBE) approach\(^5\) to investigate the spin relaxation in (111) GaAs quantum wells, with all the relevant scatterings included. The electron density and temperature dependences of the spin relaxation along the \(\hat{z}\) axis under different conditions (e.g., distinct gate voltages and impurity densities, etc.) are studied. Two peaks can be observed in the electron density dependence of the SRT when the temperature is low under proper gate voltages. One is the Coulomb peak while the other is the cancellation peak. The location of the former is insensitive to the gate voltage while that of the latter is modulated by the gate voltage. Under the proper gate voltage, these two peaks merge together and the SRT is largely prolonged. However, when the temperature increases, only one peak, the normal density peak, is observed. In the temperature dependence of the SRT, the Coulomb peak can be observed if the cancellation effect is excluded under a large gate voltage. When the cancellation effect is present under a relatively smaller gate voltage, it together with the temperature dependence of the scattering lead to a single peak in the temperature dependence of the SRT. The effect of impurities on the temperature dependence of the spin relaxation is investigated. Under the large gate voltage the Coulomb peak is destroyed by the impurities. However, under the small gate voltage where the cancellation effect is present, a peak always exists even with very high impurity density. As the cancellation of the DP term only happens in the quantum-well plane, we also investigate the anisotropic spin relaxation by varying the spin-polarization direction. It is shown that when the spin-polarization direction is tilted from the \(\hat{z}\)-axis to the in-plane one, the cancellation peak gradually disappears due to the weakening of the cancellation effect.

This paper is organized as follows. In Sec. II, we first introduce the KSBEs and then investigate the spin relaxation in (111) GaAs quantum wells by means of KSBEs. We summarize in Sec. III.

II. KSBEs AND NUMERICAL RESULTS

We start our investigation from the \(n\)-type (111) GaAs quantum wells. The well width \(a\) is taken to be 7.5 nm. At this width including only the lowest subband is sufficient in our investigation. The spin-polarization direction is along the \(\hat{z}\)-direction except otherwise specified and the initial spin polarization is 0.025. The Rashba parameter \(\alpha\) is chosen to be 28 Å\(^2\)\(^8\). The other parameters (\(\gamma\), effective electron mass and g-factor, etc.) are the same as those in Ref.\(^{37}\). The KSBEs read\(^5\)\(^8\):

\[
\dot{\rho}_k = \dot{\rho}_k^{\text{coh}} + \dot{\rho}_k^{\text{scat}}.
\]

Here \(\rho_k\) are the single-particle density matrices, whose off-diagonal elements \(\rho_k^{\text{coh}}\) represent the spin coherence and the diagonal elements \(f_{k\sigma}\) are electron distribution functions with spin \(\sigma\). Here \(\sigma = 1/2\) \((-1/2)\) denotes the spin polarization along the \(\hat{z}\) \((-\hat{z})\) axis. \(\rho_k^{\text{coh}}\) are the coherent terms describing the spin precession of electrons and \(\rho_k^{\text{scat}}\) are the scattering terms including the electron-acoustic/longitudinal optical phonon, electron-impurity and electron-electron Coulomb scatterings. Their expressions are given in detail in Refs.\(^{27}\) and \(^{37}\).

To numerically solve the KSBEs, the initial conditions are set as

\[
\rho_k(t = 0) = F_{k\uparrow} + F_{k\downarrow} / 2 + F_{k\uparrow} - F_{k\downarrow} \hat{n} \cdot \sigma.
\]

Here \(\hat{n}\) is the spin-polarization direction. \(F_{k\uparrow}\) \((F_{k\downarrow})\) stand for the Fermi distribution functions of electrons with spin-up \((-\downarrow)\) determined by the polarized electron density and temperature. By numerically solving the KSBEs, one can obtain the single-particle density matrices at any time \(t\). Then, the SRT can be obtained from the temporal evolution of the spin polarization

\[
P_{\text{SRT}}(t) = \sum_k \text{Tr}[\rho_k(t) \hat{n} \cdot \sigma] / N_e,
\]

with \(N_e\) being the total electron density.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2}
\caption{(Color online) Electron density dependence of the SRT at different gate voltages. The temperature \(T = 20\) K and the impurity density \(N_i = 0\).}
\end{figure}

A. Electron density dependence of SRT

We first study the electron density dependence of the SRT with different gate voltages at \(T = 20\) K. The impurity density is zero. The results are plotted in Fig. 2. From the figure, one finds that when \(E_z < 82\) kV/cm, two peaks are present. When \(E_z\) increases from 80 to...
81 kV/cm, the peak labeled with an arrow shifts towards the lower density regime (from $N_e = 3.6 \times 10^{11}$ to $2.1 \times 10^{11} \text{ cm}^{-2}$), while the location of the other peak remains unchanged at about $N_e = 0.2 \times 10^{11} \text{ cm}^{-2}$. When $E_g \geq 82 \text{ kV/cm}$, only one peak can be observed at the location $N_e = 0.2 \times 10^{11} \text{ cm}^{-2}$. Moreover, the peak for the case with $E_g = 82 \text{ kV/cm}$ has a substantially longer SRT (up to ~800 ns).

We first concentrate on the cases with $E_g < 82 \text{ kV/cm}$ where two peaks can be observed. The peak, with its location remaining unchanged at $\sim 0.2 \times 10^{11} \text{ cm}^{-2}$ (the corresponding Fermi temperature for this density is $T_F \approx 8 \text{ K}$), is the Coulomb peak in the density dependence\(^{26,31}\) (here the Coulomb scattering is dominant). The location of the Coulomb peak is insensitive to $E_g$, as the Coulomb scattering is independent of $E_g$ and the variation rate of inhomogeneous broadening versus $N_e$ is marginally affected by $E_g$ (since the cancellation effect happens in the regime far away from the Coulomb peak). The other peak (labeled with an arrow), with its location being tunable by $E_g$, is just the cancellation peak. Based on Eq. (5), one can obtain the condition of the gate voltage with which the cancellation effect can take place in the density dependence. It is found that $k_F^2 < 0$ when $E_g > E_c^g = 82.8 \text{ kV/cm}$. Therefore, when $E_g > E_c^g$, $\langle \Omega^2_{\perp}(\mathbf{k}) \rangle$ increases with $N_e$ monotonically and no cancellation effect takes place. When $E_g < E_c^g$, with the increase of $E_g$, $k_F^2$ decreases and thus the cancellation peak shifts towards the lower density regime. That is exactly what is shown by the cases with $E_g < 82 \text{ kV/cm}$ in Fig. 2. In addition, for the low temperature such as 20 K here, Eq. (6) can be utilized to estimate the location of the cancellation peak by setting $k_F = k_e$ ($k_F$ is the Fermi momentum). The corresponding electron densities $N_e^c$ obtained from $k_F$ are $3.8 \times 10^{11}$ and $2.5 \times 10^{11} \text{ cm}^{-2}$ for the cases with $E_g = 80$ and 81 kV/cm respectively. When $E_g = 82 \text{ kV/cm}$, the two peaks merge together [the estimation from Eq. (6) gives $N_e^c = 1.1 \times 10^{11} \text{ cm}^{-2}$] and the SRT is markedly prolonged. However, when $E_g = 83 \text{ kV/cm}$, the cancellation effect is absent, causing the inhomogeneous broadening to be stronger than the case with $E_g = 82 \text{ kV/cm}$ and to increase with $N_e$ monotonically. Therefore, the SRT with $E_g = 83 \text{ kV/cm}$ becomes smaller and the peak remaining at $N_e = 0.2 \times 10^{11} \text{ cm}^{-2}$ is again caused by the increase of Coulomb scattering strength with increasing $N_e$ in the nondegenerate regime. In this sense, this peak can be classified as the Coulomb peak.

We then investigate the electron density dependence of the SRT under different temperatures with $E_g < E_c^g$, e.g., 80 kV/cm. The results are shown in Fig. 3(a). It is noted that with the increase of $T$ from 20 to 50 K, the Coulomb (cancellation) peak gradually shifts towards the higher (lower) density regime with increasing (decreasing) magnitude. Moreover, when $T \geq 50 \text{ K}$, only one peak can be observed, with the magnitude decreasing with the increase of $T$. To facilitate the understanding of these phenomena, we further plot the corresponding electron density dependences of the inverse of the inhomogeneous broadenings, i.e., $\langle \Omega^2_{\perp}(\mathbf{k}) \rangle^{-1}$, in Fig. 3(b). The shift of the Coulomb peak with $T$ from 20 to 50 K is understood by noticing that the electron density corresponding to the crossover of the nondegenerate and degenerate regimes increases with increasing $T$ [it is noted that with increasing $N_e$, $1/\tau_{ee}$ increases in the nondegenerate regime but decreases in the degenerate regime\(^{26}\)]. The increase in the magnitude of the Coulomb peak with increasing $T$ is due to the enhancement of the Coulomb scattering (and the electron-phonon scattering) as well as the small variation of the inhomogeneous broadening with $T$ in the regime where the peak appears [as shown in Fig. 3(b)]. With the increase of $T$, the cancellation peak decreases in magnitude and shifts towards the lower density regime, as the corresponding peak in the $\langle \Omega^2_{\perp}(\mathbf{k}) \rangle^{-1}$ curve does [Fig. 3(b)]. Finally when $T$ exceeds 50 K, the cancellation peak is absent and the single peak is the normal density peak rather than the Coulomb peak as the electron-phonon scattering also comes into effect. The magnitude of this peak decreases with increasing $T$ because the increase of the inhomogeneous broadening suppresses the scattering strength.
B. Temperature dependence of SRT

We investigate the temperature dependence of the SRT in this section. The study is first performed for high-mobility case under different gate voltages. The electron density is taken to be $1 \times 10^{11}$ cm$^{-2}$ and the impurity density is set to be zero. The results are plotted in Fig. 4(a).

It is shown from the figure that when $E_z > 83$ kV/cm, a peak exists in the temperature dependence of the SRT and shifts towards the lower temperature regime with the decrease of $E_z$. When $E_z = 82$ kV/cm, the SRT decreases with $T$ monotonically. However, as $E_z$ further decreases, a peak reappears and shifts towards the higher temperature regime. Nevertheless, when $E_z$ is as small as 75 kV/cm, the SRT increases with increasing $T$ monotonically and no peak is observed in the temperature regime under investigation.

$$\langle \Omega^2_z \rangle = \frac{1}{N_i} \sum_{k} \frac{k_z^2}{k_F^2}$$

The peak observed in the $\tau_e$-$T$ curve with $E_z > 83$ kV/cm in Fig. 4(a) is actually the Coulomb peak in the temperature dependence, as revealed previously in other systems. Here the Fermi temperature of the electrons is $T_F = 40$ K, and the Coulomb peak is located in the range of $(T_F/2, T_F)$. With the decrease of $E_z$, the Coulomb peak shifts towards the lower temperature regime, and finally disappears when $E_z$ approaches 82 kV/cm. This phenomenon is caused by the increase in the decreasing rate of $\langle \Omega^2_z \rangle$ versus $T$, as shown in Fig. 4(b). In fact, when $E_z = 82$ kV/cm, which is almost equal to $E_z$, the in-plane DP term is substantially cancelled at $T = 0$ and $\langle \Omega^2_z \rangle$ decreases with increasing $T$ effectively. When $E_z < 82$ kV/cm, the cancellation effect arises and a peak of the SRT reappears. The left-hand side of the peak is caused by both the increase of the scattering strength and the decrease of the inhomogeneous broadening with increasing $T$, while the right-hand side caused by the increase of the inhomogeneous broadening with increasing $T$. It is noted that the location of this peak can be either lower or higher than $T_F$, differing from the case of the Coulomb peak. In fact, this peak is located at a temperature relatively higher than the temperature corresponding to the peak in the $\langle \Omega^2_z \rangle$-$T$ curve, due to the increase of the scattering strength with increasing $T$. With the decrease of $E_z$, the peak of the SRT shifts towards the higher temperature regime, as the cancellation effect takes place at a higher temperature. Nevertheless, when $E_z$ is as small as 75 kV/cm, the SRT increases with increasing $T$ monotonically. That is because at this small gate voltage, the cancellation effect is expected to happen at a high temperature beyond the regime under study. However, under this high temperature the cancellation effect becomes very weak. As a result, $\langle \Omega^2_z \rangle$ decreases with increasing $T$ mildly in the temperature regime under study [as shown by the solid curve in Fig. 4(b)]. This mild decrease of $\langle \Omega^2_z \rangle$ is suppressed by the increase of the scattering strength with increasing $T$ and consequently the SRT increases with increasing $T$ monotonically.

![FIG. 4: (Color online) (a) The temperature dependence of the SRT in different gate voltages. (b) The corresponding temperature dependence of $\langle \Omega^2_z \rangle$. The electron density $N_e = 10^{11}$ cm$^{-2}$ and the impurity density $N_i = 0$.](image)

To understand the features depicted above, we first specify at what gate voltage the cancellation effect can take place in the temperature dependence. From Eq. (5), a critical value of $E_z$ is obtained to be 82.1 kV/cm (referred to as $E_z^c$) by setting $k_z = k_F$. When $E_z > E_z^c$, $k_z < k_F$ ($E_z < E_z^c$), $k_z^2 < k_F^2$ ($E_z > k_F^2$) and the cancellation effect is absent (present). Moreover, when $E_z < E_z^c$, the smaller $E_z$ is, the higher temperature at which the cancellation effect is expected to happen becomes. However, due to the high temperature, the cancellation effect becomes very weak. We further plot the temperature dependence of $\langle \Omega^2_z \rangle^{-1}$ under different gate voltages in Fig. 4(b). The properties of the $\langle \Omega^2_z \rangle^{-1}$-$T$ curves are modulated by the gate voltage in the way presented in the above theoretical analysis.

We now investigate the effect of impurities on SRT under two typical gate voltages, $E_z = 85$ and 80 kV/cm, larger and smaller than $E_z^c$ respectively. The temperature dependences of the SRT with different impurity densities are plotted in Fig. 5(a) and (b). In Fig. 5(a), the peak disappears when even small amount of impurities are present. However, in contrast, a peak always exists even at very high impurity density but shifts towards the lower temperature regime with the increase of $N_i$ in...
impurities as shown in Fig. 5(a). This scenario is the

Fig. 5(b). These phenomena are understood as follows. With the increase of \( N_i \), the electron-impurity scattering becomes dominant. However, the electron-impurity scattering is insensitive to \( T \) when \( T \) is low. Therefore, the temperature dependence of the SRT is determined by the variation of the inhomogeneous broadening with \( T \). As a result, for the case with \( E_z = 85 \) kV/cm where the inhomogeneous broadening increases with increasing \( T \) monotonically, the Coulomb peak is destroyed by the impurities as shown in Fig. 5(a). This scenario is the same as what predicted in (001) GaAs quantum wells. However, for the case with \( E_z = 80 \) kV/cm the peak always exists due to the cancellation effect. With the increase of \( N_i \), this peak shifts towards the location corresponding to the peak in the \( \langle \Omega_z^2(k) \rangle^{-1} \cdot T \) curve.

C. Anisotropic spin relaxation

As shown by Eqs. (1)–(3), the cancellation of the effective magnetic field only happens to the in-plane component. Therefore the spin relaxation will show anisotropic property with the change of the polarization direction. We vary the angle \( \theta \) between the spin-polarization direction and the \( \hat{z} \)-axis to investigate this anisotropy. The electron density dependence of the SRT with different spin-polarization orientations. \( \theta \) is the angle between the spin-polarization direction and the \( \hat{z} \)-axis. The peak appears at \( N_e \sim 3.2 \times 10^{11} \) cm\(^{-2} \) is the cancellation peak and that at \( N_e \sim 0.2 \times 10^{11} \) cm\(^{-2} \) is the Coulomb peak in density dependence, as discussed previously in Fig. 5(a). With the increase of \( \theta \), the cancellation peak gradually disappears. That is because the inhomogeneous broadening contributed by the \( \hat{z} \)-component of the effective magnetic field becomes more important and the cancellation effect becomes weaker. In fact, when the spin-polarization direction is not in the \( \hat{x}-\hat{y} \) plane (\( \theta = \pi/2 \)), e.g., along the \( \hat{x} \)-axis, the inhomogeneous broadening, depicted by \( \langle \Omega_z^2(k) \rangle = \langle \Omega_y^2(k) + \Omega_z^2(k) \rangle \), increases monotonically with the increase of \( N_e \), as shown in the inset of Fig. 6. Therefore, when \( \theta = \pi/2 \), only the Coulomb peak, but no cancellation peak, is observed in the density dependence. The similar anisotropy of the spin relaxation also exists in the temperature dependence. For example, it is found that the peak in the dotted curve in Fig. 5(b) gradually disappears when the spin-polarization direction is tilted from the \( \hat{z} \)-direction to the in-plane one.

III. CONCLUSION

In conclusion, we have investigated the spin relaxation in \( n \)-type (111) GaAs quantum wells by numerically solving the fully microscopic KSBEs. Differing from the widely investigated (100) GaAs quantum wells, in (111) GaAs quantum wells, the in-plane effective magnetic field from the DP term can be suppressed to zero on a special momentum circle under the proper gate voltage due to the cancellation of the Dresselhaus and Rashba spin-orbit

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**FIG. 5:** (Color online) Temperature dependence of the SRT with different impurity densities. \( N_i = 1 \times 10^{11} \) cm\(^{-2} \). (a) \( E_z = 85 \) kV/cm and (b) \( E_z = 80 \) kV/cm.

**FIG. 6:** (Color online) Electron density dependence of the SRT with different spin-polarization orientations. \( \theta \) is the angle between the spin-polarization direction and the \( \hat{z} \)-axis. \( T = 30 \) K, \( E_z = 80 \) kV/cm and \( N_i = 0 \). Inset shows the electron density dependence of \( \langle \Omega_z^2(k) \rangle^{-1} \) for the case with \( \theta = \pi/2 \).
couplings. When the spin-polarized electrons mainly distribute around this special circle, the in-plane inhomogeneous broadening is small. Under this condition the spin relaxation can be suppressed, especially for that along the growth direction of the quantum well. This cancellation effect may cause a peak (the cancellation peak) in the density or temperature dependence of the SRT. In this work, we mainly investigated the electron density and temperature dependences of the spin relaxation along the quantum-well growth direction. Besides, we also studied the anisotropic property of the spin relaxation by varying the spin-polarization direction.

In the electron density dependence of the SRT, two peaks can be observed under proper gate voltages at low temperature: one is the well-studied density peak\textsuperscript{30,31} (also referred to as the Coulomb peak in the present work due to the absence of the impurity) and the other is the cancellation peak. The location of the cancellation peak can be tuned by the gate voltage. When the two peaks merge together, the SRT is markedly prolonged. However, if the gate voltage is large enough and the cancellation effect is absent, the Coulomb peak can be observed. Besides, even under a relatively small gate voltage, with the increase of temperature, the originally existing cancellation peak disappears due to the weakening of the cancellation effect and consequently only one peak can be observed.

In the temperature dependence of the SRT, the presence of the cancellation effect also depends on the gate voltage. When the cancellation effect is excluded under a large gate voltage, the Coulomb peak in the temperature dependence, as revealed previously in the systems where the cancellation effect is absent\textsuperscript{27-31} can be observed. When the cancellation effect arises with the decrease of the gate voltage, it together with the temperature dependence of the scattering lead to a single peak of the SRT in the temperature dependence. We further investigated the effect of impurities on the temperature dependence of the SRT. Under the large gate voltage where the cancellation effect is absent, the Coulomb peak is easily destroyed by impurities. On the contrary, under the small gate voltage where the cancellation effect is present, a peak always exists even with very high impurity density.

We also showed the anisotropy of the spin relaxation with respect to the spin-polarization direction. It was found that the cancellation peak gradually disappears when the spin-polarization direction is tilted from the quantum-well growth direction to the in-plane one. This is because the inhomogeneous broadening contributed by the effective magnetic field along the growth direction of the quantum well becomes more important and the cancellation effect becomes weaker.

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\textsuperscript{*} Author to whom correspondence should be addressed; Electronic address: mwwu@ustc.edu.cn.

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