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The drift of electron spin helices in an external in-plane electric field in GaAs quantum wells is studied by means of time-resolved magneto-optical Kerr microscopy. The evolution of the spin distribution measured for different excitation powers reveals that, for short delay times and higher excitation powers, the spin helix drift slows down while its envelope becomes anisotropic. The effect is understood as a local decrease of the electron gas mobility due to electron collisions with nonequilibrium holes within the excitation spot and is reproduced well in the kinetic theory framework. For larger delay times, when the electrons constituting the spin helix and nonequilibrium holes are separated by an electric field, the spin helix drift accelerates and the mobility reaches its unperturbed value again.

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I. INTRODUCTION

In two-dimensional electron gases (2DEGs), spin-orbit (SO) interaction is responsible for a broad range of phenomena, such as spin galvanic effects [1,2] or spin textures such as the persistent spin helix (PSH) [3–5]. A PSH in (001)-grown zinc-blende-type quantum wells (QWs) occurs when the parameters associated with the bulk β (Dresselhaus) [6] and structural α (Rashba) [7] inversion asymmetries are equal in strength [8–10]. GaAs QWs with modulation doping are naturally suited to balance α and β by a proper choice of doping and the well width [11]. The resulting momentum-dependent effective magnetic field \( B_{SO}(k) \) associated with the spin-orbit coupling becomes close to unidirectional, and the SU(2) spin rotation symmetry is restored in the system [9]. Under these circumstances, the dominant mechanism of spin dephasing (such as the Dyakonov-Perel mechanism for spin textures) gets suppressed and the spin helix appears to be the most long-lived spin excitation in the 2DEG with a lifetime increased by several orders of magnitude [9,12,13].

PSH texturing shows promise for spintronic applications since the spin polarization could be preserved during transport. A prominent example is the spin transistor proposed by Datta and Das that uses a gate-tunable Rashba spin-orbit interaction for the electric manipulation of the spin state [10,14,15].

However, in order to bring further robustness to more realistic spin transistors, unwanted effects caused by applied in-plane electric fields have to be considered. For example, a recent study has shown that the heating of the electron system by an in-plane electric field leads to a drift-induced enhancement of the cubic Dresselhaus parameter [16]. This, in turn, introduces temporal oscillations of the spin polarization during transport by drift and causes spin dephasing [17,18]. Additionally, spin diffusion was shown to be highly sensitive to the experimental conditions. An increased density of photoexcited carriers can result in a transition from ballistic motion to diffusive motion, leading to a decrease in the spin-diffusion coefficient [19]. On the other hand, the carrier heating, due to the applied strong in-plane electric field, increases the diffusion coefficient by more than an order of magnitude [20].

Here we develop the study of spin transport in 2DEG further. Employing time-resolved magneto-optical Kerr effect microscopy (TR-MOKE), which allows us to track the drift and evolution of spin textures in 2DEG, we show that the electron mobility is spatially inhomogeneous. The drift of an optically induced spin helix is slowed down at short delay times, which is attributed to the electron scattering by nonequilibrium holes within the excitation spot. In contrast, when the nonequilibrium holes and electrons forming the spin helix get spatially separated by an electric field, the helix drift accelerates and its mobility reaches the mobility of electrons in turn, introduces temporal oscillations of the spin polarization during transport by drift and causes spin dephasing [17,18]. Additionally, spin diffusion was shown to be highly sensitive to the experimental conditions. An increased density of photoexcited carriers can result in a transition from ballistic motion to diffusive motion, leading to a decrease in the spin-diffusion coefficient [19]. On the other hand, the carrier heating, due to the applied strong in-plane electric field, increases the diffusion coefficient by more than an order of magnitude [20].

II. EXPERIMENTAL DETAILS

The 15-nm GaAs quantum well is grown by molecular beam epitaxy on a highly n-doped [001]-oriented GaAs...
substrate. The QW is sandwiched between Al_{0.33}Ga_{0.67}As barriers, and two Si δ-doping layers are placed above the QW, providing a resident electron concentration in the QW. The wafer is patterned in a 15-μm-wide Hall-bar geometry with a back gate and AuGeNi Ohmic in-plane contacts, with the dimensions between the in-plane contacts \(d_1 = 1.107 \text{ mm}\) and \(d_2 = 1.145 \text{ mm}\), respectively. To ensure maximum spin lifetimes, all measurements are performed with a back-gate voltage \(U_{BG} = -1 \text{ V}\) and a lattice temperature of 3.5 K. The photoluminescence, magnetotransport, and transient reflectivity measurements allow us to estimate the electron concentration of \(n_0 = 9 \times 10^{11} \text{ cm}^{-2}\), mobility of \(\mu_0 = 2.5 \times 10^5 \text{ cm}^2 \text{V}^{-1} \text{ s}^{-1}\), and photocarrier lifetime of \(\tau_r > 670 \text{ ps}\), respectively [20]. The corresponding Fermi energy of the electron gas is \(E_F = \frac{2\hbar v_F}{m_e} \approx 3 \text{ meV}\), where \(m^* = 0.064 m_e\) is the effective mass [21], \(m_e\) is the free electron mass, and \(\hbar\) is the reduced Planck constant.

Pulses with temporal width of \(\sim 35 \text{ fs}\) derived from a 60-MHz mode-locked Ti:sapphire oscillator are used to perform TR-MOKE measurements. They are split into pump and probe, and modified by gratings-based pulse shapers [22], resulting in pulses with a bandwidths of \(\sim 0.5 \text{ nm}\) and temporal resolution of \(\sim 1 \text{ ps}\). Pump pulses are modulated between left \(\sigma^-\) and right \(\sigma^+\) circular polarization by an electro-optic modulator. The probe pulses are linearly polarized, collinear with the pump pulses, and focused on the sample surface through a 50× microscope objective. The FWHM diameter of pump and probe pulses is \(w_0 = 3 \pm 0.1 \mu\text{m}\) and \(1 \pm 0.1 \mu\text{m}\), respectively. Kerr rotation is measured with balanced photodiodes connected to a lock-in amplifier referenced to the electro-optic modulation frequency. The pump reflection is filtered out by a monochromator, whereas the probe polarization is resolved using a half-wave plate and Wollaston prism. The delay time \(t\) between the pump and probe pulses is adjusted by a mechanical delay stage with \(t_{\text{max}} = 1.7 \text{ ns}\). The spatial overlap of the pump with the fixed and centered probe is adjusted through a lateral translation of the input lens of the beam-expanding telescope in the pump path [23,24]. The pump and probe photon energies are chosen based on the spectral response of the 2DEG at maximum spatial and temporal overlap; see Ref [25]. All measurements are performed with the pump photon energy set to \(E_p = 1.57 \text{ eV}\) and the peak power density varied in the range of \(I_p = (1.4 - 7.4) \text{ MW/cm}^2\). Using 2.6% absorbance of the QW [26] and 30% Fresnel coupling loss, the range of optically injected electron densities is estimated to \(0.43 n_0 < n_{\text{op}} < 2.2 n_0\). The probe photon energy is \(E_{pr} = 1.53 \text{ eV}\) with a pulse peak irradiance of \(I_{pr} = 2.36 \text{ MW/cm}^2\).

**III. RESULTS AND DISCUSSION**

The circularly polarized pump creates a local spin polarization of electrons which evolves into spin helix. The in-plane electric field applied to the structure causes the drift of electrons and modifies the pattern of spin polarization. The spin polarization of holes can be neglected because of the fast spin relaxation, typically a few picoseconds [27].

Figure 1(a) shows the measured evolution of the spin polarization distribution along the \(x\) axis \(S_x(x, y = 0, t)\) and along the \(y\) axis \(S_y(x = 0, y, t)\) for an in-plane electric field of \(E_{x0} = -3.4 \text{ V/cm}\). The constructed dashed lines highlight the temporal precession.

(a) Spin polarization micrographs \(S_x(x, 0, t)\) and \(S_y(0, y, t)\) for an in-plane electric field of \(E_{x0} = -3.4 \text{ V/cm}\). The constructed dashed lines highlight the temporal precession. (b) Extracted time dependence of the center of Gaussian \(x(y)t\) and the squared FWHM \(w_{x0}^2(t)\) (c). The solid lines in (b) and (c) are linear fits to the data for short decay times.

\[
S_x(x, 0, t) = A e^{-\frac{4(\omega_4 x - \omega_{g4})^2}{w_4^2}} \cos(q_4 x + \omega_4 t),
\]

\[
S_y(0, y, t) = A e^{-\frac{4(\omega_4 y - \omega_{g4})^2}{w_4^2}} \cos(q_4 y + \omega_4 t),
\]

where \(A\) is the spin polarization amplitude; \(q_4(t) = 2\pi / \lambda_{so,x}(t)\) is the wavevector associated with spin texture, \(\lambda_{so,x}(t) = \lambda_{so,x}(t) w_{x0}(t)^2 / (w_{y0}(t)^2 - w_{y0}^2)\) is the momentary spin precession length,

\[
\omega_{x0}(t) = -2 m^* h^2 d_{dr,x0} \beta_3\]

is the angular frequency of spin precession at fixed \(x(y)\) [28], that leads to a finite spin phase velocity at large times [18]; \(\beta_3\) is the constant of \(k\)-cubic...
spin-orbit interaction, \(x_G(y_G)\) describes the temporal evolution of the spin polarization center due to drift velocity, whereas the \(w_{x(y)}\) is the FWHM of the Gaussian envelope.

Figures 1(b) and 1(c) show the temporal evolution of the spin helix center \(x_G(y_G)\) and the squared FWHM \(w_{x(y)}^2\), respectively, extracted using Eq. (1). At first glance, one would expect that the temporal evolution of the center of the spin helix envelope [Fig. 1(b)] should follow a linear dependence \(x_G(y_G) = u_{dr,x(y)}t\), where \(u\) is the electron mobility. However, the experimental dependence of \(x_G(y_G)\) on time shows more complex behavior: up to \(t < 500\) ps it follows the linear dependence, whereas for delay times above \(t > 500\) ps it deviates towards higher values. Specifically, the average velocity in the time interval \(500\) ps to \(1000\) ps is \(v_{dr,x(y)} \approx 12\) km/s and exceeds the average velocity in the first \(500\) ps by \(\approx 60\%\). The reason for the drift slow-down at large times, when the electron-hole separation is considerable, might be the space-charge effect discussed in Ref. [29].

Even more complex is the time evolution of the width of the Gaussian envelope; see Fig. 1(c). One can expect that the envelope should grow in time due to diffusion according to

\[
w_{x(y)}^2(t) = w_0^2 + 16 \ln(2) D_s t,
\]

where \(D_s\) is the spin-diffusion coefficient and \(w_0\) is the initial FWHM defined by the laser spot. The experimental data presented in Fig. 1(c) follow partly the trend already seen in Fig. 1(b): up to \(t < 500\) ps the temporal evolution of the Gaussian envelope follows the calculated one while strongly deviates towards higher values until roughly \(1\) ns.

The anomalous temporal evolution of \(x_G(y_G)\) and \(w_{x(y)}^2\) depicted in Figs. 1(b) and 1(c) is present for any in-plane applied electric fields in the range \((0.8 - 4.3)\ \text{V/cm}\). Similar anomalous evolution of \(w_{x(y)}^2\) with time was also observed in Ref. [20]. Possible microscopic mechanisms responsible for this evolution based on macroscopic screening of the external electric field in undoped QWs [29], electron gas heating by electric field and modification of the mobility and diffusion coefficient [20] have been discussed. We now want to put our results into perspective with the work reported by Yakota et al. [29]. In Ref. [29], a slowing down of the drift velocity of photo-generated electron-hole pairs in external electric fields has been attributed to space-charge fields effectively lowering the applied external electric field. These findings are in line with rigid shift models for this space-charge field developed, e.g., by Zhao et al., [30]. However, in our present work we analyze the situation of a high-mobility two-dimensional electron gas at low temperatures. These conditions are particularly well suited to identify excitation-induced reductions of the mobility of electrons which is the main point of the present paper. In contrast, the work in Refs. [29,30] focus on the dynamics in undoped QWs at room temperature. In this situation, the mobility is mostly limited by phonon scattering anyway such that the reduction of the mobility upon photoexcitation is negligible. As a result, those studies emphasize the impact of space-charge fields which are comparatively small in our study. The small reduction of the drift velocity seen at larger delay times of about \(1\) ns might arise from such space-charge effects, though.

Here, we develop and test the idea that the observed anomalous drift and broadening of the spin helix envelope originates from the change of the electron mobility due to scattering of electrons with optically excited holes. Under focused excitation, the electron mobility exhibits a spatial and temporal dependence which we model according to

\[
\mu(r,t) = \frac{\mu_0}{1 + \tau_s/\tau_{eh}(r,t)}
\]

where \(r = (x,y)\) is the in-plane coordinate, \(\mu_0 = \tau_s e/m^*\) is the electron mobility in the absence of photocarriers, which is determined from magneto-transport measurements, \(\tau_s\) is the time of electron scattering by impurities or phonons and \(\tau_{eh}\) is the electron-hole scattering time. The latter is expected to be inversely proportional to the local density of holes \(n_h(r,t)\), \(1/\tau_{eh}(r,t) = \sigma_{eh} v_F n_h(r,t)\), where \(\sigma_{eh}\) is the electron-hole scattering cross-section for the two dimensional system and \(v_F\) is the Fermi velocity of electrons.

Evolution of the spin distribution function \(S(r,t)\) is governed by the kinetic equation [5,20]

\[
\frac{\partial S}{\partial t} = D_s \frac{\partial^2 S}{\partial r^2} - \nabla S \cdot \left( \frac{\partial}{\partial r} \cdot \mu E \right) S = 4 D_s m^*(\alpha - \beta) / h^2,
\]

where \(D_s\) is the spin diffusion coefficient, \(\Gamma\) is a tensor containing Dyakonov-Perel spin-relaxation-rates (note that it is diagonal in the chosen coordinate frame \((x,y)\)). It has components \(\Gamma_{xx} = D_s [2m^*(\alpha - \beta) / h^2], \Gamma_{xy} = D_s [2m^*(\alpha + \beta) / h^2], \Gamma_{yy} = \Gamma_{xx} + \Gamma_{yy}\) [31]. \(A\) is the tensor describing the spin precession during diffusion with nonzero components \(\Lambda_{xy} = 4 D_s m^*(\alpha + \beta) / h^2, \Lambda_{yy} = -4 D_s m^*(\alpha - \beta) / h^2\).

Figure 2(a) schematically shows the evolution of the spatial distributions of optically oriented electrons and holes in an in-plane electric field for different delay times. At \(t = 0\), the photoexcited electrons and holes have identical 2D Gaussian distributions (inherited from the pump pulses) that overlap spatially. The electrons, being surrounded by holes, have a reduced mobility \(\mu(r,t) < \mu_0\), due to the increased scattering. In the in-plane electric field, the electrons and holes start to drift in the opposite directions, which leads to their spatial separation. The stronger the in-plane electric field is, the faster the separation happens. Note that the drift velocity of holes is much smaller than that of electrons, due to larger effective mass. Besides, the hole density decays with the recombination time \(\tau_r\), which is illustrated in Fig. 2(a) by gray circles of different brightness. The electrons that have left the excitation spot where the hole density is high exhibit less scattering. Therefore, they have higher mobility and drift velocity than the electrons that are still inside the excitation spot. This leads to a stretching of the shape of the electron distribution along the drift direction. The experimental 2D plots in Fig. 2(b) track the spatial distribution of spin polarization for three different times. The elongation of the spin polarization distribution is clearly visible for \(t = 325\) ps and is even more pronounced for \(t = 990\) ps.

Figure 2(c) shows the spin distributions calculated by solving the kinetic equation (4) with the initial conditions \(S_z(x, y, 0) = S_0 \exp[-4 \ln(2)(x^2 + y^2)/w_0^2], S_x(x, y, 0) = S_y(x, y, 0) = 0\), where \(w_0 = 3\ \mu\text{m}\) is the FWHM of pump laser beam. It is assumed that the electron mobility is affected by photogenerated holes and varies in space and time according to Eq. (3). The
FIG. 2. Two-dimensional distribution of spin polarized photocarriers under the influence of an applied in-plane electric field (along $y$-direction) for different delay times. (a) Model showing the spatial separation of optically injected electrons and holes, resulting in a spatially and temporally dependent carrier mobility. (b) 2D micrographs of the electron spin polarization distribution showing an elongation of the initially isotropic Gauss distribution along the direction of the applied electric field. (c) 2D spin polarization distribution obtained from the solution of kinetic Eq. (4) that incorporates spatial and temporal variation of $\mu(r,t)$.

electron-hole scattering cross-section was taken to be $\sigma_{eh} = 0.2 \times 10^{-12}$ cm$^2$/($v_F \tau_i$), as determined from fits of the dependence of our findings from the excitation density. The hole distribution was assumed to have the form $n_h(x, y, t) = n_0 \exp\left[-4 \ln(2)(x^2 + y^2)/w_0^2\right] \exp(t/\tau_R)$, where $\tau_R = 670$ ps is the recombination time and the peak hole density was taken $n_0 = 1.5 \times 10^{12}$ cm$^{-2}$. Diffusion of the holes is neglected due to the large hole mass. The effect of holes on the electron spin diffusion coefficient is also neglected, since the latter is mostly limited by electron-electron collisions. Therefore, the spin diffusion coefficient is assumed to be constant, and its value was determined from the fit of the FWHM evolution measured at low excitation powers, $D_s = 83$ cm$^2$/s. Rashba and Dresselhaus parameters $\alpha = 0.9 \pm 0.1$ meV Å and $\beta = 2.1 \pm 0.1$ meV Å were extracted previously from the periods of spatial spin precession, as described in Sec. II. The result of the numerical solution well reproduces all the features of the spin distribution observed in the experiment.

To further corroborate the effect of photoexcited holes on the electron mobility, we have compared the spin distributions measured at different excitation powers corresponding to different photocarrier densities. Fig. 3(a) shows the $S_z$ distribution along the $y$ direction after a delay time $t = 210$ ps for an applied in-plane electric field of $E_y = 4.3$ V/cm. The short delay time is chosen because at longer delay times the Gaussian distribution is too much distorted. A qualitative inspection of the data reveals that an increase in excitation density reduces the depth of the trough (negative $S_z$) and increases the peak amplitude (positive $S_z$), see the vertical blue arrows. This corresponds to a shift of the Gaussian envelope center $y_G$ closer to the excitation point ($y = 0$ $\mu$m), as indicated by the horizontal blue arrow, and simultaneously to an increase of the FWHM $w_y$. Such effects are well reproduced by the kinetic theory, see Fig 3(b). The decrease of $y_G$ and increase of $w_y$ are explained by the decrease of the average electron drift velocity and increase of the drift velocity spread with the increase of the local hole density. Figure 3(c) shows the same type of data measured when $E_y = 0$ V/cm. In this case, increasing the optical pumping does not affect the spin distribution, as both the Gaussian center $y_G$ and the FWHM $w_y$ are not modified. This observation indicates that the increase
of photocarrier density does not affect the spin diffusion coefficient.

The quantitative analysis of the spin distributions depicted in Fig. 3 are performed using Eq. (2). The results of the simulation permit to extract the parameters $y_G$ and $w_y$. Fig. 4(a) shows the dependence of the center $y_G$ of the Gaussian envelope on the initial local photocarrier density for various $E_y$ in-plane electric fields in the range of $(0.8-4.3)\,\text{V/cm}$. The delay time was tuned to maintain constant $y_G$ shift. As was mentioned above, for a given electric field the increase in photocarrier density results in a decrease of the $y_G$ value, indicating the shift of the Gaussian envelope closer to the excitation point. The $y_G$ decrease is more pronounced in the case of higher electric fields. Figure 4(c) shows the evolution of the FWHM $w_y$ for the same conditions as in the Fig. 4(a), where $w_y(0)$ is the FWHM for each individual delay time in the absence of the in-plane electric field. $w_y$ was chosen in order to compensate for the diffusion at different delay times. It increases with increasing optical power and the applied in-plane electric field $E_y$, leading to significant changes (as high as 20%) in the FWHM for $E_y = 4.3\,\text{V/cm}$ and $n_{op} = 2.0 \times 10^{12}\,\text{cm}^{-2}$. Figures 4(b) and 4(d) show the corresponding plots obtain using kinetic theory and agree well with experimental data.

IV. CONCLUSIONS

In conclusion, we have analyzed drifting spin helices in a 2DEG under the influence of SO coupling. The main finding is that a spatial inhomogeneity of the electron mobility has to be taken into account to properly explain the dynamics after photoexcitation. It arises from the scattering of electrons with optically excited holes and substantially slows down the initial electron velocity. The analysis of the evolution of the spin distribution for different excitation powers and shorter delay times shows that for higher excitation powers, the drift of the spin distribution is slowed down while its diffusion-induced spread becomes anisotropic. The effect is attributed to the local decrease of the electron mobility due to their collisions with non-equilibrium holes within the excitation spot and is explained in the framework of kinetic theory. In contrast, for larger delay times, when the non-equilibrium holes and electrons are separated by the electric field, the electron drift accelerates and the electron mobility reaches the value in the absence of photocarriers. This local character of the electron mobility may have a negative impact for future spintronic devices, as a drifting spin wave (spin helix) in the presence of an optical excitation is distorted spatially which may lead to potential information loss.

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