

Optical control of electron-spin texture based on modulation of spin-orbit interaction in a modulation-doped GaAs/(Al, Ga)As quantum well

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We demonstrate the optical control of the spatial spin texture in a modulation-doped GaAs/AlGaAs quantum well based on the modulation of the spin-orbit interaction. Spatiotemporal evolution of electron spins with irradiation by a continuous-wave laser that does not induce interband transitions of electrons reveals an increase in the Rashba coefficient and the spin diffusion coefficient, in contrast to the decrease in these coefficients due to optical doping by increasing the electron-spin excitation density. From the difference between the absorption energy and the emission energy, the carrier density in the quantum well increases. This indicates that the continuous-wave laser irradiation causes photoactivation of naturally deactivated electrons in the doping layer of AlGaAs, and therefore the Rashba spin-orbit interaction increases due to the increased asymmetry of the quantum well profile.

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I. INTRODUCTION

The momentum-dependent spin-orbit (SO) effective magnetic field acting on electron spins enables the manipulation of the electron-spin state locally. In the persistent spin helix (PSH) with exact SU(2) symmetry, the SO effective magnetic field is aligned uniaxially [1,2], resulting in the complete suppression of spin relaxation due to spin-independent scattering, including D'yakonov-Perel' spin relaxation [3]. In a zinc-blende-type quantum well (QW) on the (001) plane such as a GaAs/AlGaAs QW, when the two types of SO interactions, the Rashba [4] and Dresselhaus [5] SO interactions, are equal in magnitude, a PSH state with an in-plane uniaxial effective magnetic field is achieved. The electron spins injected locally diffuse and precess around the effective magnetic field, forming and preserving a striped spin pattern. The development of spin measurement techniques with high spatial resolution and high time resolution has made it possible to observe spatiotemporal spin dynamics and spatially periodic structures of spins directly [6–11]. This opens up the potential for

information processing, such as spin-based wave parallel computing, using the characteristics exhibited by the wavelike structure of electron spins [12].

Semiconductors are excellent at converting electron spins and light polarization based on optical selection rules. Because of this, the direct generation of spatial spin structures using spatial polarization structures of light has been demonstrated [13–16], and programmable generation is also possible [16]. On the other hand, the spatial structure of the spin pattern preserved in semiconductors is determined by the effective magnetic field configuration originating from the SO interaction. Thus, to control the spatial spin structure in a solid, the modulation of the SO interaction is required. The Rashba SO interaction can be modulated by an out-of-plane electric field [17,18], and the modulation of the spatial spin structure has been observed using an electric field [7,9,19]. On the other hand, there is the possibility of optically controlling the spatial spin structure without preparing electrodes. Modulation of the Rashba SO interaction due to optically excited carrier spins by a laser pulse has been observed in several studies [10,19,20]. However, in these cases, because interband transitions generate not only electrons but also holes, the electric field is screened due to the excited carriers [21], resulting in the small modulation of the Rashba SO interaction [20]. Furthermore, the temporary modulation of the SO interaction due to the optically excited carriers generated by the laser pulse disappears by carrier recombination.

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In this study, we demonstrate the optical modulation of the SO interaction using a cw laser that does not induce interband transitions. The time evolution of the spatial spin distribution during cw light irradiation at different laser powers is measured using the time- and spatially resolved magneto-optical Kerr effect. We estimate the carrier density from photoluminescence excitation spectra, as well as the SO parameters, spin diffusion coefficient, and spin lifetime from the spatiotemporal evolution of electron spins. Because the screening effect of the Rashba SO interaction due to the excited carrier does not occur, the modulation of the SO parameter is larger than that caused by pulse irradiation, resulting in a clear difference in the distributed spin pattern. The variation of carrier density and the spin diffusion coefficient reveals that the Rashba SO interaction is enhanced by doped electrons in the QW layer due to the optical activation of the remaining electrons in the doping layer.

II. EXPERIMENTAL METHODS

The sample studied here is a modulation-doped, 20-nm-thick (001) GaAs/AlGaAs single QW grown by molecular beam epitaxy. A 20-nm-thick, highly Si-doped AlGaAs layer is placed on top of the QW with an undoped 35-nm-thick AlGaAs spacer layer, providing a high-mobility two-dimensional electron gas (2DEG). The 2DEG density $n = 4.1 \times 10^{15} \text{ m}^{-2}$ and electron mobility $\mu = 130 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ are determined using Hall and conductivity measurements at 5 K after light irradiation. The one-sided modulation-doped structure induces an asymmetric profile of the QW, leading to the induction and

enhancement of the Rashba SO interaction. The spatiotemporal evolution of electron spins is measured using a time- and spatially resolved magneto-optical Kerr rotation (KR) technique. The photon energies of the pump and probe beams are set to 1.553 eV, which is slightly above the resonant absorption energy, and the absorption edge of approximately 1.53 eV. The outputs of the pump and probe beams are set to 50 and 60 μW , respectively. The pump beam is converted to a repetition of left- and right-handed circular polarization at 50.147 kHz by a photoelastic modulator. The pump and probe beams are focused on the sample using an objective lens. The sigma widths of the pump and probe beams are $\sigma_{\text{pp}} = 1.1 \text{ } \mu\text{m}$ and $\sigma_{\text{pr}} = 0.9 \text{ } \mu\text{m}$. A circularly polarized pump beam excites out-of-plane spin polarization at time $t = 0$ and spatial origin $(x, y) = (0, 0)$. A linearly polarized probe beam detects the out-of-plane spin component $S_z(x, y, t)$ as polar Kerr rotation by varying the relative delay time and position between the pump and probe beams using a mechanical delay line and a scanning mirror, respectively. A cw laser with a wavelength of 980 nm is used as the control light since the sample, which contains GaAs and AlGaAs, does not exhibit interband absorption at this wavelength. The diameter of the control light is adjusted using a lens pair, and it is aligned coaxially with the pump beam using a beam splitter. The control light covers a sufficiently larger area than the pump beam, with its $1/e^2$ spot size being approximately 44.2 μm . A setup of photoluminescence (PL) measurement is also installed in the reflection beam path. The PL spectra are obtained using a spectrometer with a focal length of 300 mm, equipped with a charge-coupled device. The Kerr

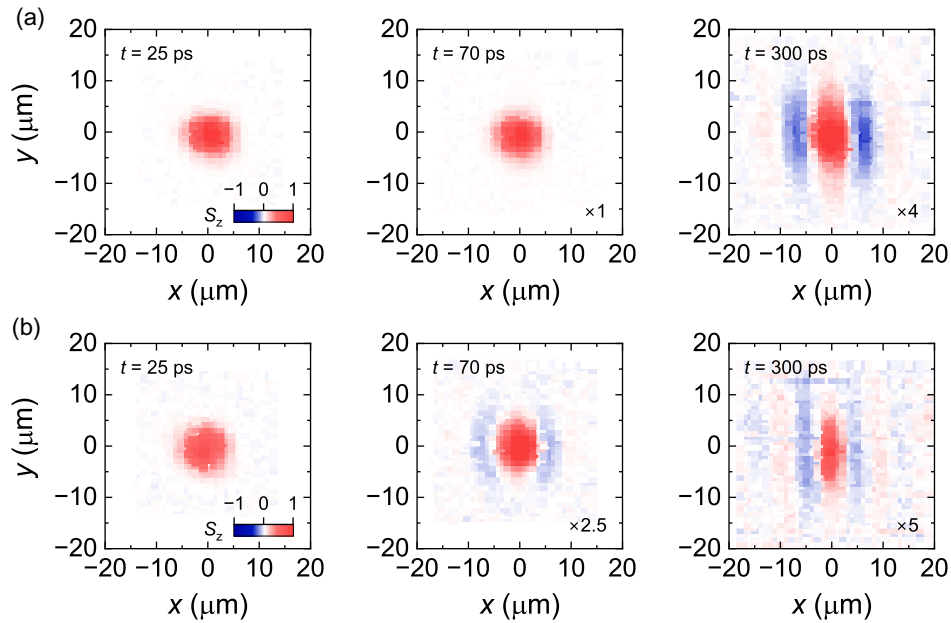


FIG. 1. Spatial distribution of electron spins $S_z(x, y)$ at 25, 70, and 300 ps after excitation (a) without light irradiation and (b) with light irradiation. Normalization factors are indicated at the bottom-right of each map.

rotation measurement and PL measurement can be selected by switching the mirror installed on the flip mount. Optical measurements are performed at approximately 8 K using a cryostat with optical access (see the Appendix for details on the experimental setup).

III. RESULTS AND DISCUSSION

We measure the spatiotemporal evolution of spin distribution under conditions with and without control light irradiation from a cw laser. Figure 1(a) shows the spin map without control light irradiation at different time intervals, while Fig. 1(b) shows the spin map under control light irradiation at an intensity of 10.89 mW. Immediately after excitation ($t = 25$ ps), spins align in the up-spin state near the spatial origin. Then, spins diffuse over time and precess due to the SO effective magnetic field, which depends on the momentum vector. In the absence of control light irradiation, the SO effective magnetic field approximates the PSH state. Consequently, electron spins moving in the x -direction precess, whereas those moving in the y -direction maintain their spin state, resulting in a stripe-shaped spin spatial structure. In contrast, under control light irradiation, the spin distribution exhibits an elliptical shape at 70 ps. Furthermore, as shown in the spin distribution at $t = 300$ ps, the spin precession length λ_{SO} in the case of light irradiation becomes shorter. From the spin distribution along the x -direction, λ_{SO} values of 13.43 ± 0.51 μm without light irradiation and 9.23 ± 0.24 μm with light irradiation are obtained.

To estimate changes in the strength of the SO interaction caused by control light irradiation from a cw laser, we measure the time-space spin map while applying an external magnetic field. Figure 2(a) shows the time evolution of the spin distribution along the x -direction $S_z(x, y = 0, t)$ with an external magnetic field $B_{\text{ext}} = 289$ mT applied along the y -direction, under varying control light intensities. The in-phase point represents the balance between the SO effective magnetic field acting on diffusive electrons and the external magnetic field. From the shift in the in-phase point of the spins, the SO coupling parameter $-\alpha + \tilde{\beta}$ can be estimated [22], where $\alpha < 0$ is the Rashba coefficient, $\tilde{\beta} = \beta_1 - \beta_3 > 0$ is the Dresselhaus parameter, and β_1 and β_3 are the linear and cubic Dresselhaus coefficients, respectively. The parameter, plotted as a function of control light intensity P and shown as squares in Fig. 2(c), reveals that $-\alpha + \tilde{\beta}$ increases with control light intensity, which is consistent with the observed decrease in spin precession length λ_{SO} by control light irradiation [Fig. 1(b)]. Similarly, the SO coupling parameter $-\alpha - \tilde{\beta}$ is obtained from the time shift of the in-phase point in the spatiotemporal evolution of the spin distribution along the y -direction $S_z(x = 0, y, t)$ under an external magnetic field applied in the x -direction, as shown in Fig. 2(b). Circles in Fig. 2(c) show the dependence of $-\alpha - \tilde{\beta}$ on control light

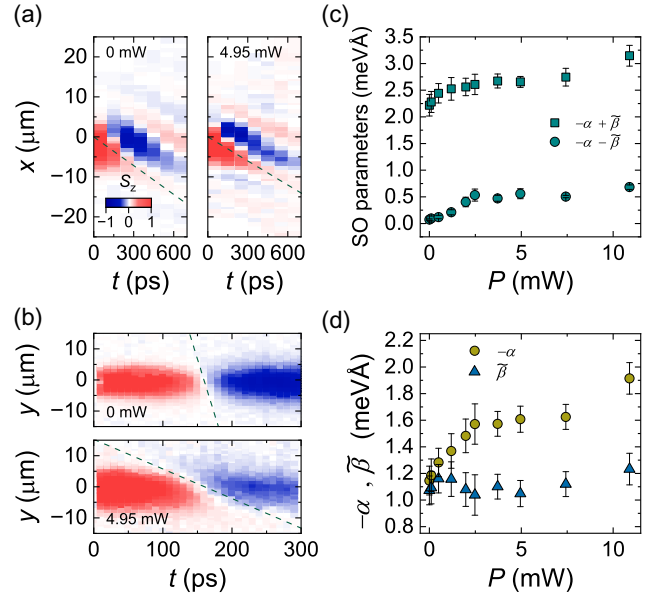


FIG. 2. (a) Time-space map $S_z(x, y = 0, t)$ with external magnetic field $B_y = 289$ mT at no light irradiation and light irradiation of 4.95 mW. (b) $S_z(x = 0, y, t)$ with external magnetic field $B_x = 289$ mT at no light irradiation and light irradiation of 4.95 mW. Dashed lines represent the in-phase point of spin precession. (c) Control light intensity dependence of SO parameters $-\alpha + \tilde{\beta}$ and $-\alpha - \tilde{\beta}$. (d) Control light intensity dependence of Rashba parameter $-\alpha$ and Dresselhaus parameter $\tilde{\beta}$.

intensity. As the light intensity increases, the SO parameters deviate from the PSH condition $-\alpha + \tilde{\beta} = 0$. The individually estimated strengths of the Rashba coefficient $-\alpha$ and the Dresselhaus parameter $\tilde{\beta}$, shown in Fig. 2(d), indicate that $-\alpha$ increases up to $P = 2.5$ mW, after which it saturates. This trend of increase in $|\alpha|$ resulting from the light irradiation is in contrast to the results of optical doping, where $|\alpha|$ decreases due to the screening of the electric field caused by the generation of both electrons and holes [10,20]. The observed increase in $|\alpha|$ suggests an enhanced electric field in the QW due to increased asymmetry.

To clarify the effects of control light irradiation from a cw laser, we perform photoluminescence (PL) and PL excitation (PLE) measurements. Figure 3(a) shows the PL and PLE spectra under various light intensities. With increasing light intensity, the energy peak of the emission band E_g^* shown in the PL spectra and the absorption edge E_{abs} shown in PLE spectra exhibit a redshift and blueshift, respectively. These show that the amount of energy difference between them, corresponding to the Stokes shift, increases by light irradiation, and specifically that the Fermi energy E_F increases. E_g^* and E_{abs} in the QW are plotted as functions of light intensity, as shown in Fig. 3(b). E_g^* and E_{abs} vary markedly at a low light intensity and are almost constant at high light intensity. The carrier density of the QW, estimated from the Stokes shift [23,24]

shown in Fig. 3(c), is up to 1.45 times higher within the measurement range with light irradiation compared with that without light irradiation. Because the control light with the wavelength of 980 nm does not induce carriers originating from the interband excitation, this increase in the carrier density is likely to be due to the photoactivation of naturally deactivated electrons from Si donors in the doping layer and their inflow into the QW by light irradiation. When the electrons are additionally induced in the QW from the doping layer by light irradiation, the electric field is enhanced due to the increase in electrons in the QW and positive ionized donors. This results in the enhancement of Rashba SO interactions due to the structural inversion asymmetry. These pictures explain all of the experimental observations without contradiction, including the enhancement of the Rashba coefficient, the increase in carrier density, and the redshift of the luminescence energy due to the enhancement of the quantum confined Stark effect by irradiation with control light. The saturation of parameter changes at high light irradiation power can be understood as being due to the upper limit on the number of residual carriers in the doping layer. The difference between the effect of light irradiation on Rashba modulation in this study and that of optical doping in previous studies [10,20] is due to the difference in the location of the positive charge generated by light irradiation. In optical doping, which involves interband absorption, both electrons and holes are generated, and they are spatially separated in the QW so as to screen the electric field in the QW. On the other hand, the light irradiation used in this study does not induce holes, but instead increases the number of positively ionized donor impurities in the doping layer, enhancing the electric field in the QW. As the direction of the Coulomb electric field induced by light irradiation is opposite, the Rashba modulation effect is also opposite. While the cubic Dresselhaus coefficient, which is proportional to the 2DEG density n expressed as $\beta_3 = -n\gamma_D\pi/2$, where $\gamma_D < 0$ is the bulk Dresselhaus coefficient, increases, the Dresselhaus parameter $\tilde{\beta} = \beta_1 - \beta_3$ is almost constant with respect to the irradiation light intensity. This indicates that the linear Dresselhaus coefficient $\beta_1 = -\gamma_D\langle k_z^2 \rangle$, where $\langle k_z^2 \rangle$ is the mean square of the electron wave number along the growth direction, also increases with increasing irradiation light intensity because of the enhancement of the quantum confinement effect.

Next, we evaluate the variation in the spin diffusion coefficient and spin lifetime due to the control light irradiation. Figure 4(a) shows the time evolution of the spin distribution $S_z(x, y = 0, t)$ measured at the light irradiation intensities of $P = 0$ and $P = 10.89$ mW. By light irradiation, the spatial expansion of electron spins is accelerated compared with nonirradiated conditions, resulting in the fast formation of the helical spin pattern. The spatiotemporal evolution of electron spins can be described by the

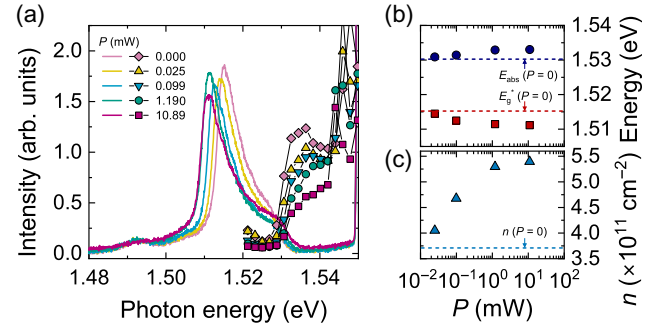


FIG. 3. (a) PL and PLE spectra under various light intensities. Solid lines and symbols represent PL and PLE spectra, respectively. (b) Irradiation light intensity dependence of absorption energy E_{abs} and energy peak of emission from QW E_g^* . (c) Irradiation light intensity dependence of carrier density n .

equation of

$$S_z(x, t) = A(t) \exp\left(\frac{-x^2}{2\sigma^2(t)}\right) \cos\left(\frac{2\pi x}{\lambda_{\text{SO}}}\right) + A_O(t) \exp\left(\frac{-x^2}{2\sigma_O^2(t)}\right), \quad (1)$$

where $A(t)$ and $\sigma(t)$ are the amplitude and the sigma width of the Gaussian-shaped distribution of 2DEG spins, and the second term is the other contributions, such as the residual spin in bulk GaAs [20]. Figure 4(b) shows the time evolution of $\sigma^2(t)$ and the slope of $\sigma^2(t)$ indicates the spin diffusion coefficient D_s , which is expressed by the relationship $\sigma^2(t) = \sigma_0^2 + 2D_s t$. The time variation of $\sigma^2(t)$ increases with increasing light intensity, indicating that D_s increases with the light irradiation. As shown in Fig. 4(c), the spin diffusion coefficient D_s increases monotonically with light intensity. This can be explained by the decrease in the electron-electron scattering rate τ_{ee}^{-1} in a degenerated system. The experimentally obtained D_s is much smaller than the charge diffusion coefficient $D_e = 1.9 \text{ m}^2/\text{s}$, extracted from the measured carrier density and mobility using $D_e \approx \mu E_F/e$, that is, $D_s \ll D_e$. This indicates that the spin Coulomb drag (SCD) due to the electron-electron scattering, which affects the spin resistivity, reduces spin diffusion significantly [23–27]. The maximum D_s value of $0.1 \text{ m}^2/\text{s}$ obtained in our experiment is approximately 1 order of magnitude smaller than D_e , consistent with previous experimental reports of D_s reduction due to the SCD [26,27]. In our experiment, because the excitation energy of electron spins is high compared with the resonance excitation energy, the electron-electron scattering is enhanced [28,29]. The ratio of D_e to D_s can be described as $D_e/D_s \approx 1 + |\rho_{\uparrow\downarrow}|/\rho$, where $|\rho_{\uparrow\downarrow}|/\rho$ is the ratio of spin resistivity to charge resistivity and the normalized spin susceptibility χ_s/χ_0 is set to 1 for high electron density [26,30]. $|\rho_{\uparrow\downarrow}|/\rho$ is described by τ_p/τ_{ee} using the spin drag

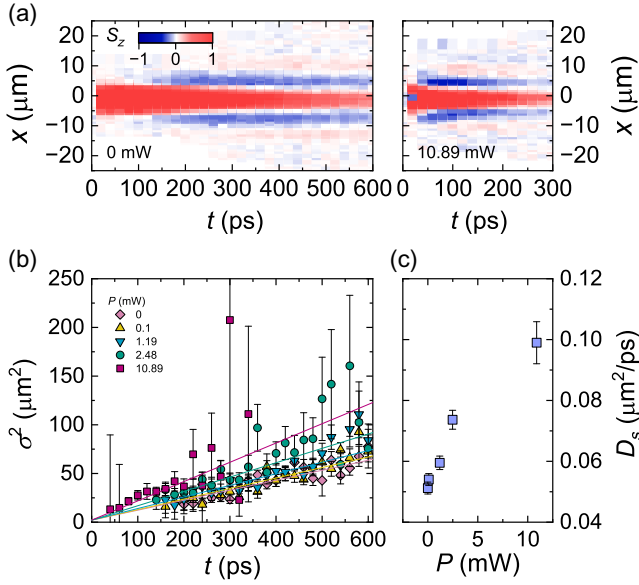


FIG. 4. (a) Time-space map $S_z(x, y = 0, t)$ under no light irradiation and under light irradiation of 10.89 mW. (b) The time evolution of $\sigma^2(t)$ at various light irradiation intensities. Solid lines are fitting curves. (c) Light irradiation intensity dependence of spin diffusion coefficient D_s .

coefficient $\gamma = \tau_{ee}^{-1}$, where τ_p is the momentum scattering time. In the case of $D_s \ll D_e$, the ratio τ_p/τ_{ee} can be approximated as D_e/D_s , indicating that the D_e and D_s are linked to τ_p and τ_{ee} , respectively. Therefore, we discuss the spin diffusion coefficient using the expression $D_s \approx \tau_{ee} v_F^2/2$, where $v_F = \hbar\sqrt{2\pi n}/m^*$ is the Fermi velocity, analogous to the expression $D_e \approx \tau_p v_F^2/2$ for degenerate electrons. For a degenerate 2DEG system, τ_{ee} is proportional to n [19,31], and consequently, D_s is proportional to n^2 . Here, although the mobility should also increase proportionally to $n^{1.5}$ [32,33], the contribution is negligible because the electron-electron scattering remains dominant. At the maximum light irradiation intensity in our experiment ($P = 10.89$ mW), D_s is 1.93 times larger than in the case without light irradiation, which is in good agreement with the value of 2.10 estimated from the square of the change in carrier density.

Figure 5(a) shows the time evolution of the spin amplitude $A(t)$ at various light irradiation intensities, where $A(t)$ is obtained by fitting Eq. (1) to the time-space maps of spins, such as those shown in Fig. 4(a). The lifetime of the helical spin pattern τ_{heli} is estimated by fitting $A(t)$ to an expression that includes the diffusion term as in $A(t) \propto \frac{\exp(-t/\tau_{\text{heli}})}{(\sigma_0^2 + 2D_s t)}$, where the experimentally obtained values of D_s and $\sigma_0^2 = \sigma_{pp}^2 + \sigma_{pr}^2$ are used for fitting. With increasing light irradiation intensity, the helical spin relaxation rate τ_{heli}^{-1} increases, as shown in Fig. 5(b). The ratio of lifetimes with and without light irradiation τ_{heli}

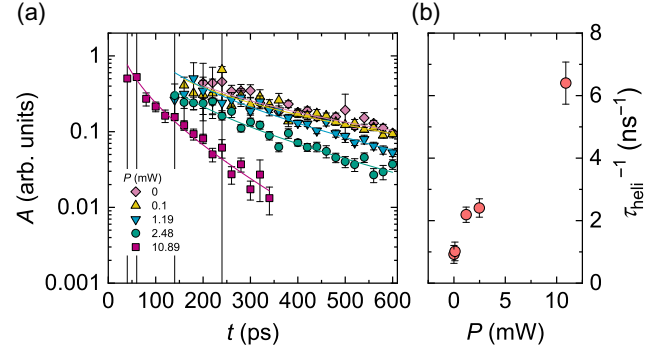


FIG. 5. (a) Time evolution of spin amplitude $A(t)$ extracted by the fitting of time-space spin maps at different excitation densities. Solid lines are fitting curves. (b) Irradiation light intensity dependence of spin lifetime τ_{heli} .

($P = 0$)/ τ_{heli} ($P = 10.89$) is 7.6. τ_{heli}^{-1} near the PSH condition is determined as follows [6]:

$$\tau_{\text{heli}}^{-1} \approx \frac{2D_s m^2 \{(-\alpha - \tilde{\beta})^2 + 3\beta_3^2\}}{\hbar^4}. \quad (2)$$

The spin diffusion coefficient D_s has varied by a factor of 1.9 times, and the SO parameter $(-\alpha - \tilde{\beta})^2 + 3\beta_3^2$, where $\beta_3 = -n\gamma_D\pi/2$ is estimated using $\gamma_D = -11 \text{ eV \AA}^3$ [34] and n is obtained from PL and PLE measurements, has varied by a factor of 2.5 times due to light irradiation. This suggests that both of these contribute to the enhancement of the spin relaxation rate.

IV. CONCLUSIONS

In conclusion, we demonstrate optical control of the SO interaction using a cw laser in a modulation-doped GaAs/AlGaAs QW. By employing time- and spatially resolved magneto-optical Kerr measurements with an external magnetic field, we reveal a significant enhancement of the Rashba SO parameter under cw illumination, accompanied by modifications in the spin diffusion coefficient. The light irradiation used in this study does not induce holes, but instead increases the number of positively ionized donor impurities at the doping layer, enhancing the electric field in the QW. This is unlike the optical doping of previous studies, which screens the electrical field due to the Coulomb coupling of separated electrons and holes. PL and PLE spectroscopy confirm that the increase in carrier density is due to the optical activation of deactivated Si donors, which is consistent with the enhancement of the Rashba SO interaction due to the variation of the electric field in the QW. Our results establish an optical approach to controlling the SO interaction without the need for external electrodes, offering a pathway for optically tunable spintronic devices utilizing spatial spin structures.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX: DETAILS ON EXPERIMENTAL SETUP

Figure 6 shows the schematic of the time- and spatially resolved Kerr rotation with control light irradiation. This setup is based on conventional Kerr rotation microscopy. A pulse train generated by a mode-locked Ti:sapphire laser with a repetition rate of 82 MHz and a pulse duration of approximately 100 fs is split into the pump and probe beams. After separation, these beams are spectrally filtered using gratings and slits for each beam, resulting in spectral widths of approximately 1.5 nm and pulse durations of approximately 1 ps. This enables the individual selection of the pump and probe energies, and thus the two-color

pump-probe measurement can be conducted. The pump beam is modulated at $f_P = 50.147$ kHz using a photoelastic modulator, and the probe beam is modulated using an acousto-optic modulator at $f_A = 51$ kHz. The Kerr rotation signal is detected using two photodiodes arranged in a balanced configuration, a transimpedance amplifier, and a lock-in amplifier tuned to the differential frequency $f_A - f_P$. A cw laser with a wavelength of 980 nm is used as the control light, and it is aligned coaxially with the pump beam using a beam splitter. A setup of photoluminescence (PL) measurement is also installed in the reflection beam path and can be switched on and off by turning the mirror on the flip mount. In the PL measurement, the linearly polarized light is used for excitation light and a linear polarizer in a cross-Nicol configuration is used to filter out the excitation light. In addition, a short-pass filter is used to filter out the control beam at 980 nm. We estimate the spot sizes of the pump and control beams. Figures 7(a) and 7(b) show the intensity profiles of their beams obtained by knife-edge measurement and their derivatives, respectively. By fitting with a Gaussian function [solid lines in Fig. 7(b)], the $1/e^2$ spot sizes of the pump and control beams are obtained to be $4\sigma = 4.4$ and 44.2 μm , respectively. The outputs of the pump and probe beams are set to 50 and 60 μW , respectively. Since pump power determines the excitation carrier density, we set it to a low value in this Kerr rotation microscope setup. The pump density is 330 W/cm^2 , and the excited carrier density is approximately on the order of 10^{11} cm^{-2} , accounting for the absorption coefficient. While probe power is generally set lower than pump

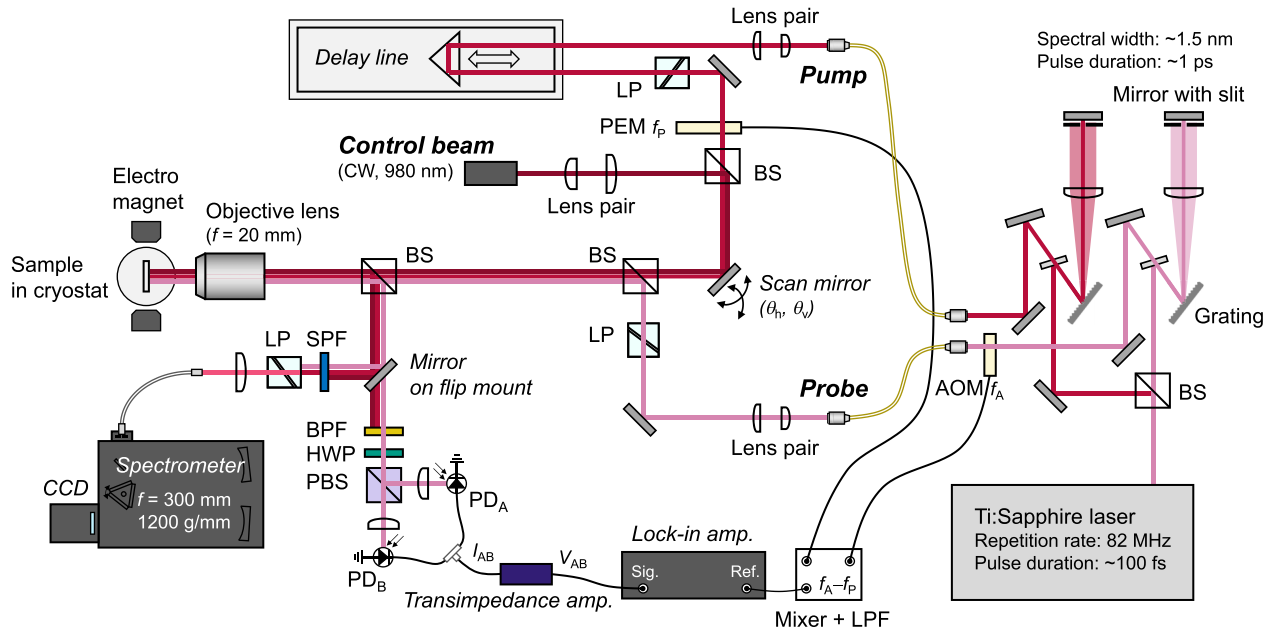


FIG. 6. Schematic diagram of the experimental setup: LP, linear polarizer; BS, beam splitter; HWP, half wave plate; PBS, polarizing beam splitter; BPF, bandpass filter; SPF, short-pass filter; PEM, photoelastic modulator; AOM, acousto-optic modulator; PD, photodiode.

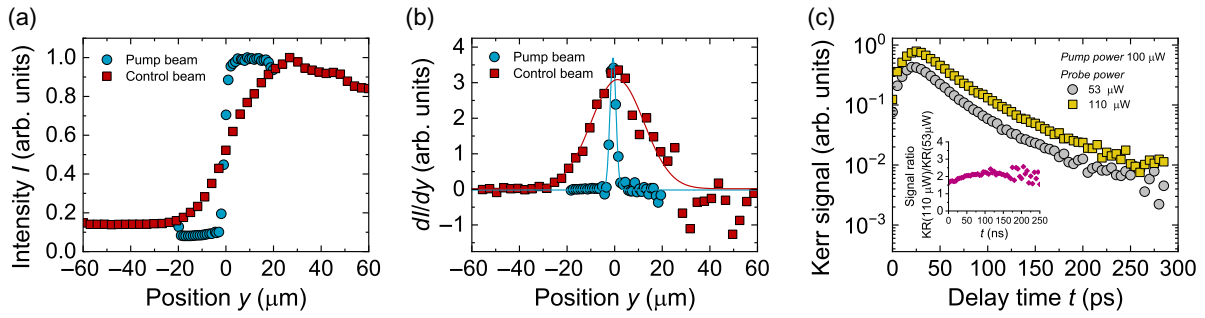


FIG. 7. (a) Intensity profile of the pump and control beams obtained by knife-edge measurement and (b) their derivatives. (c) The variation in the time evolution of the KR signal with probe power. The inset represents the ratio between the signals for these two probe conditions.

power, in this experiment, we increased the probe power to improve the signal-to-noise (SN) ratio. Figure 7(c), which presents the supplementary experimental results (obtained under slightly different conditions from the main text), shows the variation in the time evolution of the KR signal with probe power. Comparing cases where the probe power is half versus equal to the pump power, the time profile of the KR signal is unchanged, and the ratio between the signals for these two conditions [shown in the inset of Fig. 7(c)] remains roughly constant at the power ratio of the two probe beams (a factor of 2). On the other hand, the SN ratio improves particularly after 200 ps; consequently, we set the probe power to achieve a high SN ratio.

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