

Enhanced circular photogalvanic effect in oxide two-dimensional electron gas via photoelectric synergistic modulation

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We report a giant enhancement of circular photogalvanic effect (CPGE) in the oxide two-dimensional electron gas at $\text{LaAlO}_3/\text{SrTiO}_3$ and $\text{LaAlO}_3/\text{KTaO}_3$ interfaces through the synergistic ultraviolet (UV) photoexcitation and electrostatic gating. The UV illumination generates high-density photocarriers by promoting valence-to-conduction band transitions, which simultaneously increase the Fermi wave vector k_F and Fermi energy E_F . Concurrently, the gate-induced oxygen vacancy migration toward the interface amplifies the Rashba spin-orbit coupling coefficient α_R . Strikingly, the CPGE photocurrent exhibits a nonmonotonic dependence on both gate voltage and UV intensity, peaking at an optimal carrier density where k_F and α_R cooperatively enhance the spin-momentum locking. This dual control strategy achieves a CPGE responsivity of 22.71 μV for $\text{LaAlO}_3/\text{KTaO}_3$ interfaces. Our findings establish the photoelectric coupling as a powerful knob for tailoring nonequilibrium spin phenomena in quantum oxide interfaces, with direct implications for reconfigurable spintronic devices.

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I. INTRODUCTION

The circular photogalvanic effect (CPGE)—a nonlinear optical response converting circularly polarized light into spin-polarized currents—has become central to spintronics and quantum material design [1–3]. Originating from the spin-momentum locking via spin-orbit interactions, CPGE directly transforms the photon angular momentum into the directional charge flow. Recent breakthroughs demonstrate its universality across materials, unraveling spin-dependent transport physics and symmetry-breaking pathways [4–6].

In oxide two-dimensional electron gases (2DEGs), the interfacial Rashba spin-orbit coupling (SOC) drives a striking manifestation of CPGE. At $\text{LaAlO}_3/\text{SrTiO}_3$ (LAO/STO) interfaces, the visible-light excitation of spin-polarized electrons from STO's in-gap states generates helicity-dependent currents, with the efficiency governed by two critical parameters: oxygen vacancy and Rashba spin-splitting energy [6,7]. The former offers in-gap states, facilitating the excitation of spin-polarized electrons by circularly polarized light, and its spatial distribution within the substrate can be modulated by a gate voltage [8,9]. The latter enhances the efficiency of spin-to-charge conversion. In oxide 2DEGs, the spin-splitting energy is closely related to the position of Fermi surface [10]. Therefore, by adjusting Fermi surface, one can modulate the

spin-to-charge conversion efficiency and, consequently, control the intensity of CPGE [11,12].

Generally, laser illumination and electrostatic gating are powerful tools for the carrier density modulation [13–15]. Under the laser illumination, the carrier density was enhanced from 0.2×10^{13} to $0.85 \times 10^{13} \text{ cm}^{-2}$ for LAO/KTaO₃(KTO) [16]. As for the electrostatic gate, Zhang *et al.* enhanced the carrier density from 1.6×10^{12} to $6.7 \times 10^{12} \text{ cm}^{-2}$ [17]. The interplay between electrostatic gating and photoexcitation creates a dual-control paradigm for oxide 2DEGs: Gate voltages precisely engineer the Fermi surface position, while ultraviolet (UV) illumination dynamically enhances the Rashba coefficient (α_R) through the orbital-selective band hybridization.

While previous studies have established the fundamental mechanism of CPGE in oxide 2DEGs [6], the synergistic modulation of CPGE via photonic and electrostatic stimuli remains underexplored. Here, we systematically investigate the photoelectric coupling effects on CPGE at the LAO/STO and LAO/KTO interfaces. It is demonstrated that the LAO/STO exhibits a robust CPGE enhancement under the photoelectric synergy, whereas LAO/KTO initially shows the suppression under 360 nm illumination. By correlating the voltage-dependent Rashba splitting with UV illumination-tuned Fermi level, we resolve the material-specific responses rooted in the interfacial band structure and in-gap states. This work not only establishes a universal framework for the CPGE modulation in oxide heterostructures but also advances the design of multifunctional oxide spintronic devices.

II. METHODS

The 2DEGs at LAO/STO and LAO/KTO interfaces were fabricated by pulsed laser deposition following the procedure

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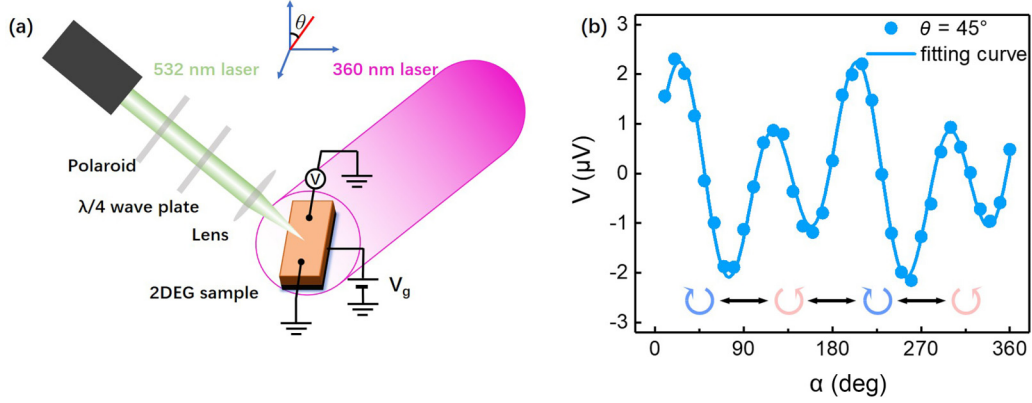


FIG. 1. (a) Sketches for the CPGE measurements. Circularly polarized incident laser is introduced into the 2DEG sample at the middle of two electrodes arranged along the x axis. The polar angle θ is fixed to 45° as constant. (b) The photovoltage as a function of polarization for the LAO/STO interfaces, collected with the 532 nm laser power = 28 mW ($P_{532} = 28$ mW).

described in previous studies [6,18]. These samples were grown in appropriately high-vacuum atmosphere without the postannealing in oxygen atmosphere to introduce oxygen vacancies. As shown in Fig. 1(a), the 532 nm laser passed successively through a polaroid and a $\lambda/4$ wave plate, and then focused on the sample surface by a lens, with a spot size of 100 μm in diameter. The distance of two electrodes is fixed to 0.8 mm. To eliminate the background voltage, we focused the polarized laser at the middle point of two electrodes. The degree of circular polarization of the incident laser was tuned by rotating the $\lambda/4$ wave plate by an angle of α . A silver electrode was deposited on the backside of substrate to enable the application of gate voltage between interface and back electrode. Here, we used the photovoltage instead of the photocurrent, which can improve the signal-to-noise ratio [6]. During UV laser illumination, the laser beam was uniformly distributed across the entire sample surface to ensure the homogeneous illumination. The transport properties of samples were characterized using a physical property measurement system.

III. RESULTS AND DISCUSSION

Figure 1(b) shows the photovoltage as a function of the rotation angle (α) of $\lambda/4$ wave plate for the LAO/STO interfaces, collected with the 532 nm laser power = 28 mW ($P_{532} = 28$ mW). To investigate the contribution of CPGE, we performed a further analysis of the V - α curve reverses. As reported, the photovoltage shows a complex periodic oscillation against α [19,20]:

$$V = V_{\text{CPGE}} \sin 2\alpha + L_1 \sin 4\alpha + L_2 \cos 4\alpha + V_0, \quad (1)$$

where V_0 is a background voltage resulting from the lateral photogalvanic effect and the effect of thermal gradients produced by laser heating, V_{CPGE} parametrizes the CPGE, which is helicity dependent, and L_1 and L_2 stem from the linear photogalvanic effect or photon drag effect, which is independent of laser helicity, respectively [5]. The V_{CPGE} signal exhibits a sign reversal upon switching the polarization from left to right circularity. The relationship between CPGE and polar angle θ has been fully demonstrated in our previous study [6].

The V_{CPGE} is zero when $\theta = 0$ and monotonically increases with θ . Here, the polar angle θ is fixed to 45° as a constant to maximize the CPGE.

To examine the modulation of external excitation sources on the interfacial CPGE, a UV laser with a wavelength of 360 nm is introduced as illustrated in Fig. 2(a). Without UV illumination [the power of UV laser (P_{360}) is zero], the V_{CPGE} demonstrates a monotonic enhancement from 0.11 to 0.93 μV with increasing the 532 nm laser intensity. This effect was significantly amplified under UV illumination, achieving a maximum relative enhancement of 34.31% at $P_{532} = 32$ mW. Consequently, the 32 mW was selected as the optimal 532 nm intensity for subsequent coupled modulation experiments.

Figure 2(b) presents the cooperative modulation combining gate voltage and UV illumination. In the depletion regime ($V_g < 0$), the photoelectric coupling effect induces a negligible enhancement on the interfacial CPGE. However, under the accumulation regime ($V_g > 0$), the V_{CPGE} shows a remarkable improvement, from 0.21 μV (without external fields) to a maximum of 1.93 μV ($P_{360} = 30$ mW, $V_g = 30$ V), representing an order-of-magnitude enhancement. The detailed polarization-dependent photovoltage variations within the blue dashed ellipse in Fig. 2(b) are explicitly displayed in Fig. 2(c). To quantitatively evaluate the photoelectric coupling effect on interfacial CPGE, a modulation percentage parameter (P) is defined as

$$P = (V_P - V_0)/V_0 \times 100\%, \quad (2)$$

where V_P and V_0 represent V_{CPGE} values with and without 360 nm excitation under identical gate voltages, respectively. The modulation phase diagram in Fig. 2(d) demonstrates that although both external fields synergistically enhance CPGE in the accumulation regime, their cooperative effect displays a nonmonotonic behavior. Maximum laser-induced enhancement ($P = 52.94\%$) is achieved at $V_g = 10$ V, indicating the optimal coupling efficiency.

Similarly, the UV laser is also employed to modulate CPGE at LAO/KTO interfaces. The LAO/KTO interface exhibits a striking departure from LAO/STO's photoelectric enhancement: 360 nm illumination suppresses CPGE by up to 70%, with suppression intensifying under concurrent

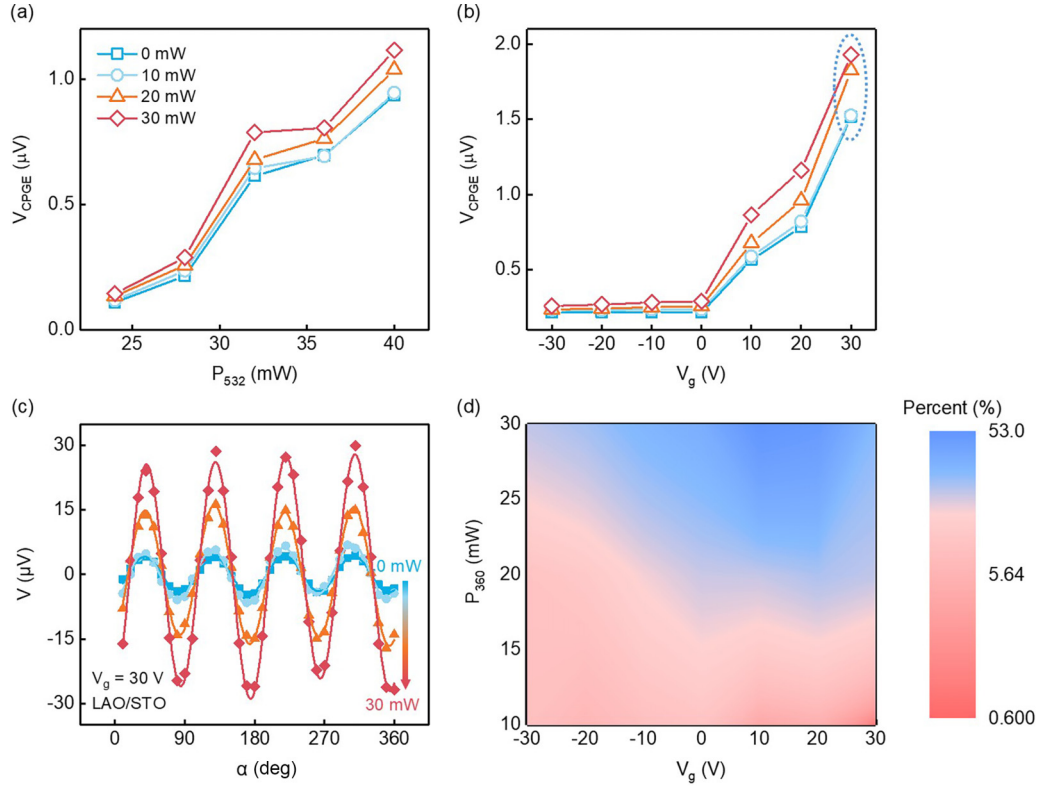


FIG. 2. (a) V_{CPGE} vs P_{532} under 360 nm laser modulation at the LAO/STO interfaces. (b) CPGE modulation via photoelectric coupling at the LAO/STO interfaces. (c) Polarization-dependent photovoltage at $V_g = 30$ V [blue dashed region in panel (b)] under varying P_{360} : from center (green, $P_{360} = 0$ mW) to periphery (red, $P_{360} = 30$ mW) with 10 mW increments. (d) Phase diagram of modulation percentage (P) vs gate voltage and 360 nm laser energy.

532 nm excitation [Fig. 3(a)]. This suppression is intensified with increasing intensities of both 532 and 360 nm lasers, reaching a maximum V_{CPGE} reduction of 70% at $P_{532} = 40$ mW ($P_{360} = 30$ mW). This response stems from UV-driven e_g -orbital hybridization in KTO-based 2DEGs [21], which disrupts Rashba coherence, whereas in STO-based interfaces, laser illumination typically promotes electrons into itinerant two-dimensional channels [18]. In contrast, the application of

a positive gate voltage alone induces a twofold increase in CPGE. Within the depletion regime, CPGE remains virtually unaltered, mirroring the weak gate modulation observed in LAO/STO systems as previously reported. Remarkably, the photoelectric coupling triggers a dramatic change of CPGE behavior. As depicted in Fig. 4(b), the UV photomodulation effect transforms from suppression to enhancement under the applied electrostatic gating. In positive bias conditions, the

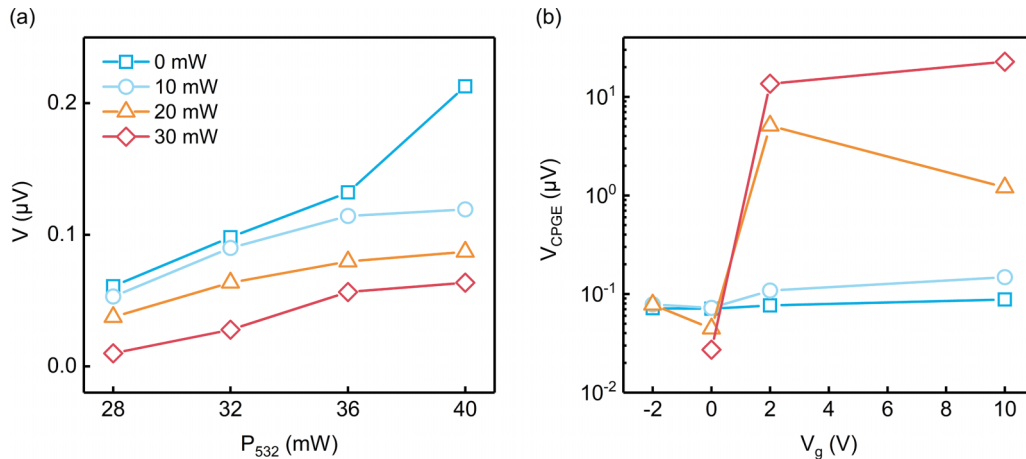


FIG. 3. (a) Modulation of 360 nm laser illumination on CPGE at the LAO/KTO interfaces without gating voltage. (b) Logarithmic V_{CPGE} response under ultraviolet photoelectric coupling modulation.

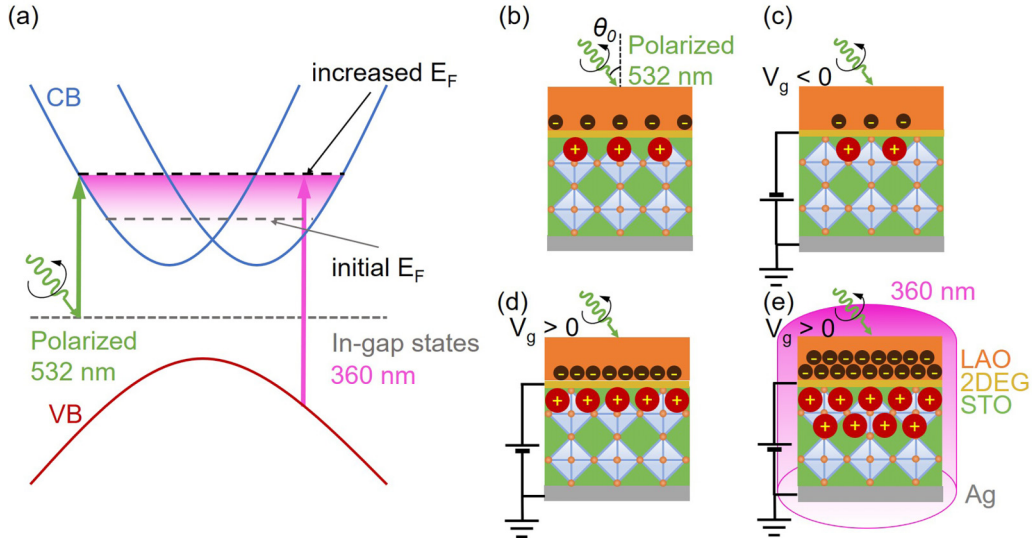


FIG. 4. Schematic of photoelectric coupling modulation on interfacial CPGE. (a) Energy band schematic under photoelectric coupling modulation at the LAO/STO interfaces. Oxygen vacancy migration across interface states: (b) the intrinsic state, (c) the depletion regime, (d) the accumulation regime, and (e) ultraviolet lasers increase the electrons in the accumulation regime.

substantial CPGE amplification emerges even at minimal gate voltages (e.g., $V_g = 2$ V), with V_{CPGE} reaching a maximum of $22.71 \mu\text{V}$ ($V_g = 10$ V, $P_{360} = 30$ mW)—representing a two-order-of-magnitude enhancement compared to the intrinsic state. For instance, at $V_g = 10$ V, the V_{CPGE} progressively is increased from $0.09 \mu\text{V}$ ($P_{360} = 0$ mW) to 0.23 , 6.20 , and $22.71 \mu\text{V}$ under $P_{360} = 10$, 20 , and 30 mW, respectively. This corresponds to an enhancement of two orders of magnitude compared to the intrinsic state ($0.07 \mu\text{V}$ at $P_{360} = 0$ mW, $V_g = 0$ V). In the depletion regime, while the photoelectric coupling yields only a modest CPGE enhancement relative to the intrinsic state, it effectively counteracts the laser-induced suppression.

The experimental findings reveal that the substantial photoelectric coupling modulation creates a diverse response in the CPGE of oxide-based 2DEGs. In the LAO/STO systems, the optical excitation universally enhances CPGE. As confirmed by our analysis, spin-polarized electrons originate from gap states [Fig. 4(a)], exhibiting oxygen vacancy characteristics [6]. From the perspective of oxygen vacancy dynamics, in the depletion regime, oxygen vacancies drift away from the LAO/STO interface under the electric field [8]. This depletion substantially reduces both oxygen vacancies and electrons at the interface, transitioning the configuration from Fig. 4(b) to Fig. 4(c). Consequently, spin-polarized electrons photoexcited from in-gap states by a polarized 532 nm irradiation diminish in quantity and must traverse extended paths to reach the interface. These prolonged trajectories cause significant recombination losses, thereby attenuating CPGE. Conversely, under accumulation bias [Fig. 4(d)], the gate-directed migration concentrates oxygen vacancies toward the interface. Spin-polarized electrons generated near the 2DEG layer experience drastically reduced travel distances, suppressing the recombination probability, substantially amplifying CPGE.

Furthermore, CPGE in oxide interfaces demonstrates a strong correlation with Rashba SOC. The Rashba spin splitting (Δ), a quantitative descriptor of interfacial coupling

strength, is expressed as $\Delta = 2\alpha_R k_F$, where k_F is the Fermi wave vector and α_R denotes the Rashba coefficient that could be modulated by gate-induced electric fields [10,22,23]:

$$\alpha_R = \frac{\hbar}{4m^2 c^2} \frac{dv}{dz}, \quad (3)$$

where m represents the effective mass of spin-polarized electrons and dv/dz corresponds to the gate-derived electric field. Positive gate voltages significantly enhance α_R ; taking the unilluminated LAO/KTO interface as an example, α_R rises from 0.13 to $2.55 \text{ meV \AA}^{-1}$ when the gate voltage is swept from 0 to 30 V, thereby amplifying the interfacial spin splitting.

Meanwhile, as Eq. (3) indicated, the Rashba spin splitting is closely related to the position of k_F , which is described as $k_F = \sqrt{2\pi n_S}$ under the near-free electron approximation in the 2D system, where n_S is the carrier density [24]. The UV laser could excite electrons in the valence band of substrate, thereby increasing the number of electrons at the interfacial potential well [Fig. 4(e)] and enhance Fermi level and k_F as shown in the violet region of Fig. 4(a). Through Hall-effect measurements, we obtained the carrier density (n_S) modulated by ultraviolet photoelectric coupling. Figure 5 further indicates the monotonic enhancement of n_S under UV photoelectric coupling modulation in both (a) LAO/STO and (b) LAO/KTO interfaces. As previously established [6], a lower n_S corresponds to a weaker V_{CPGE} . In the present study, the two samples exhibit initial carrier concentrations of 2.23×10^{13} and $4.47 \times 10^{12} \text{ cm}^{-2}$, respectively. Consequently, their V_{CPGE} values both remain relatively low, ranging from 0.1 to $0.2 \mu\text{V}$. Therefore, with a 360 nm illumination, the photoelectric coupling promotes the increase of n_S , α_R and thus spin-splitting energy, causing a significant increase in CPGE.

Notably, the 360 nm illumination alone slightly suppresses CPGE at LAO/KTO interfaces [Fig. 3(a)]. The reversal from suppression to enhancement under a modest gate voltage ($V_c \sim 2$ V) can be understood within a competition framework

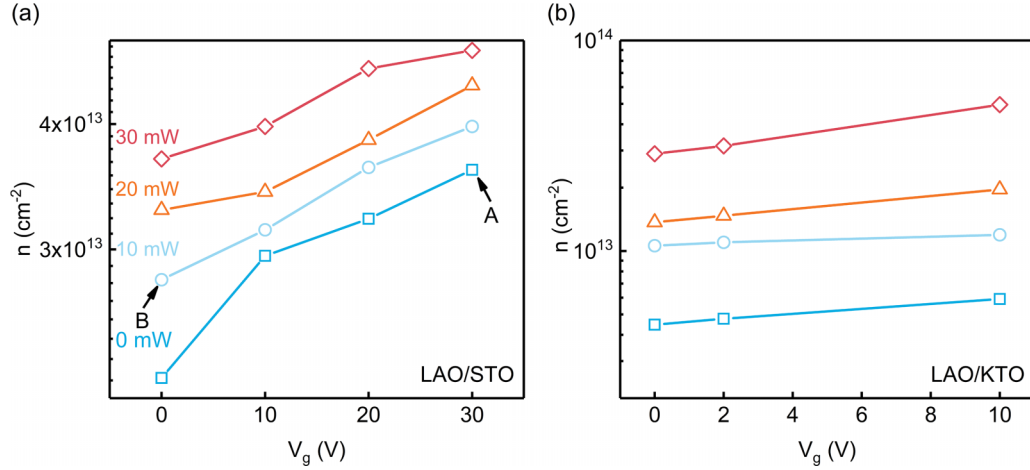


FIG. 5. Logarithmic carrier concentration of oxide-based 2DEG interfaces at room temperature: (a) LAO/STO interfaces and (b) LAO/KTO interfaces.

between UV-induced orbital hybridization and gate-induced restoration of Rashba coherence. The UV-driven e_g -orbital hybridization not only generates photocarriers but also introduces states with three-dimensional character at the interface [21,25], which disrupts the inversion asymmetry essential for strong Rashba SOC. A positive gate voltage counteracts this effect via two synergistic mechanisms: (1) It generates a vertical electric field that reconfines the photogenerated carriers back into the 2D plane, thereby restoring the structural inversion asymmetry and the “coherence” of the Rashba system; and (2) it directly enhances the Rashba coefficient α_R according to Eq. (3). The critical voltage V_c represents the point where the gate-mediated restorative effects (confinement and enhanced α_R) overcome the coherence-breaking tendency of UV-induced hybridization. Once V_g exceeds V_c , the system enters a cooperative regime where the increased carrier density (larger k_F) from UV illumination and the amplified α_R from gating jointly yield the observed orders-of-magnitude enhancement in CPGE [Fig. 3(b)].

In Fig. 5(a), the carrier density at $V_g = 30$ V without illumination (point A) is higher than that under 10 mW illumination at $V_g = 0$ V (point B). Nevertheless, the V_{CPGE} measured for the former in Fig. 2(b) is larger. Although the carrier density at point B is elevated, the UV-photogenerated carriers merely populate k_F , further enlarging the Rashba spin-splitting energy while leaving the oxygen-vacancy-like midgap states almost untouched. In contrast, at point A, the gate voltage not only enhances α_R but also drives additional oxygen vacancies toward the interface [Fig. 4(d)]. Consequently, the electrostatic gating provides a more fundamental lever for interfacial V_{CPGE} ; a substantial optical impact on V_{CPGE} can only be achieved with the assistance of gate voltage—an effect even more pronounced in the LAO/KTO system.

IV. CONCLUSION

This work establishes the photoelectric coupling as a universal control knob for the CPGE in oxide 2DEGs, offering

insights into the interplay of laser, electric fields, and material properties in spintronic applications. The UV laser excites electrons in the valence band, increasing the carrier concentration, which in turn enhances Fermi wave vector and Fermi energy. Meanwhile, the gate voltage not only promotes the migration of oxygen vacancies to the interface but also further raises Rashba coefficient. Under the synergistic effects, the CPGE significantly is enhanced. The tunability of CPGE, particularly in interfaces, suggests a potential for controlled spin-polarized current generation, paving the way for advanced oxide-based spintronic devices. These results advance reconfigurable spintronic memory devices with optical writing speeds and nonvolatile electrical readout, while providing a general framework for tailoring spin-orbit interactions in correlated quantum interfaces.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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