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Cite as: Appl. Phys. Lett. **127**, 072104 (2025); doi: [10.1063/5.0284417](https://doi.org/10.1063/5.0284417)

Submitted: 7 June 2025 · Accepted: 4 August 2025 ·

Published Online: 19 August 2025



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ABSTRACT

Odd-parity magnetoresistance (OMR), characterized by its asymmetric response to magnetic field reversal, has remained limited in practical use due to its typically small magnitude and limited control in conventional magnetic metals. Here, we report a gate-tunable OMR effect in high-mobility AlGaIn/GaN two-dimensional electron gas (2DEG) heterostructures, exhibiting a giant OMR coefficient exceeding 60%. Dual-gate control enables independent tuning of carrier density, achieving a highly linear and reversible OMR response, which is further enhanced by device geometry optimization. The effect arises from spatially engineered gradients of the Hall coefficient and magnetic-field-induced symmetry breaking. These results establish AlGaIn/GaN 2DEGs as a robust and tunable platform for high-performance OMR devices, with potential applications in nonreciprocal electronics and magnetic sensing.

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Recent advances in condensed matter physics have brought odd-parity magnetoresistance (OMR)^{1,2} to the forefront of research due to its unconventional transport characteristics. According to Onsager's reciprocity relation,^{3,4} the longitudinal resistance (R_{xx}) should be an even function of the external magnetic field H , satisfying $R_{xx}(H) = R_{xx}(-H)$. However, this symmetric behavior could be violated in magnetic systems where time-reversal symmetry is broken by spontaneous magnetization, resulting in asymmetric charge transport $R_{xx}(H) \neq R_{xx}(-H)$. For example, Kopnov and Gerber⁵ reported an OMR effect in ferromagnetic CoPd films with a non-uniform Hall coefficient, whose magnitude is below 1% under the definition $OMR = \frac{[R_{xx}(H) - R_{xx}(-H)]}{2 \times R_{xx}(0)} \times 100\%$.² Albarakati *et al.*⁶ reached an OMR value of 1.1% in $\text{Fe}_3\text{GeTe}_2/\text{graphite}/\text{Fe}_3\text{GeTe}_2$ trilayer heterostructures, where the OMR behavior came from the spin-orbit interaction of the two-dimensional material Fe_3GeTe_2 . Such OMR behaviors, distinct from classical magnetoresistance, enable enhanced sensitivity to magnetic field directionality, positioning them as a promising platform for electronic device applications. Although OMR magnitudes are typically small in metallic systems,⁵⁻⁹ Takiguchi *et al.* reported a remarkably large OMR of up to 27% in $\text{InAs}/(\text{Ga,Fe})\text{Sb}$ heterostructures,²

where the OMR effect can be electrically switched on and off, highlighting the potential of ferromagnetic semiconductor heterostructures for realizing giant and tunable OMR effects.

GaN-based semiconductor devices have achieved both low commercial production costs and impressive performance metrics, making them suitable for diverse applications.¹⁰⁻¹⁷ Among these systems, the AlGaIn/GaN heterojunction stands out for its ability to sustain a high-mobility two-dimensional electron gas (2DEG) at the interface,¹⁸ offering unique opportunities for quantum transport engineering. Our previous investigations^{19,20} have demonstrated that the magnetoresistance (MR) and electrical anisotropy of AlGaIn/GaN devices can be precisely modulated through structured gating electrodes. Furthermore, asymmetric magnetoresistance behavior has been observed in directionally inhomogeneous conducting materials characterized by spatially varying Hall coefficients along the current path.²¹ Particularly in high-mobility GaN 2DEGs, the classical Hall contribution to conductance enables the realization of magnetic-field-dependent asymmetric longitudinal resistivities.²² In this study, we designed and fabricated a dual-gate field-effect transistor structure based on the AlGaIn/GaN quantum well, without incorporating any magnetic layers. A giant OMR effect was

observed and could be continuously tuned by independently tailoring the carrier density around different Hall probe cross sections [as illustrated in Fig. 1(a)]. These findings establish a promising pathway for developing tunable OMR devices in non-magnetic materials.

The AlGaIn/GaN heterostructure films [Fig. 1(a)] used in this work were purchased from Suzhou Enkris Semiconductor Inc (mobility = $1457 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and electron density = $1.43 \times 10^{13} \text{ cm}^{-2}$ at room temperature). The sample structure is illustrated in the right panel of Fig. 1(a). The as-grown AlGaIn/GaN heterostructures were patterned into a standard Hall bar geometry using photolithography and inductively coupled plasma (ICP) etching.²⁰ A 20 nm Al_2O_3 layer was deposited by atomic layer deposition (ALD) to serve as the dielectric layer. Figure 1(a) shows the schematic structure and measurement configuration of the device. The Hall bar has a width of $W = 200 \text{ }\mu\text{m}$, with channel lengths L of $1490 \text{ }\mu\text{m}$ for Device 1 and $1250 \text{ }\mu\text{m}$ for Device 2. Two independent gate voltages (named V_{g1} and V_{g2}) were applied with both gating areas of $200 \text{ }\mu\text{m} \times 200 \text{ }\mu\text{m}$. Standard transport measurements were performed in a cryogen-free superconducting magnet system. All measurements were conducted at a temperature of 2 K with a DC of $I = 100 \text{ }\mu\text{A}$. External magnetic fields of up to 9 T were applied perpendicular to the plane of the 2DEG.

Figure 1(b) shows the longitudinal resistance R_{xx} and Hall resistances R_{H1} and R_{H2} as a function of the magnetic field in the

absence of applied gate voltages. The sample exhibits a pronounced negative magnetoresistance with a parabolic characteristic, primarily attributed to interface roughness and memory effects at the AlGaIn/GaN 2DEG interface.^{23,24} These results are consistent with our previous investigations.¹⁹ The Shubnikov-de Haas (SdH) quantum oscillations are clearly observed in the high magnetic field regions ($|H| > 5 \text{ T}$).²⁴ The rapid decrease in longitudinal resistances in low magnetic fields ($|H| < 1 \text{ T}$) indicates weak localization, a characteristic feature of this system.^{25,26} The nearly overlapping Hall resistances R_{H1} and R_{H2} indicate homogeneous carrier concentrations of the device, which can be calculated using the classical Drude model,²⁷ $n = H/\rho_{xy}e$, where e is the electron charge, and ρ_{xy} is the Hall resistivity. The calculated carrier densities are $n_1 = n_2 = 1.13 \times 10^{13} \text{ cm}^{-2}$. The fast Fourier transform (FFT) analysis of the SdH quantum oscillations is shown in Fig. 1(c). From the SdH oscillation frequency of $f = 270 \text{ T}$, the 2DEG density can be estimated using the relation $f = \hbar n/2e$, where $\hbar$ is the Planck constant. This yields a carrier density of $n = 1.3 \times 10^{13} \text{ cm}^{-2}$, consistent with the value obtained from the Drude model. The mobility $\mu = 5514 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ at $T = 2 \text{ K}$ could be obtained from the Drude model as well. The single peak in the FFT spectrum [Fig. 1(c)] indicates only one type of charge carrier in our high-quality sample, further evidencing the sample's excellent uniformity.

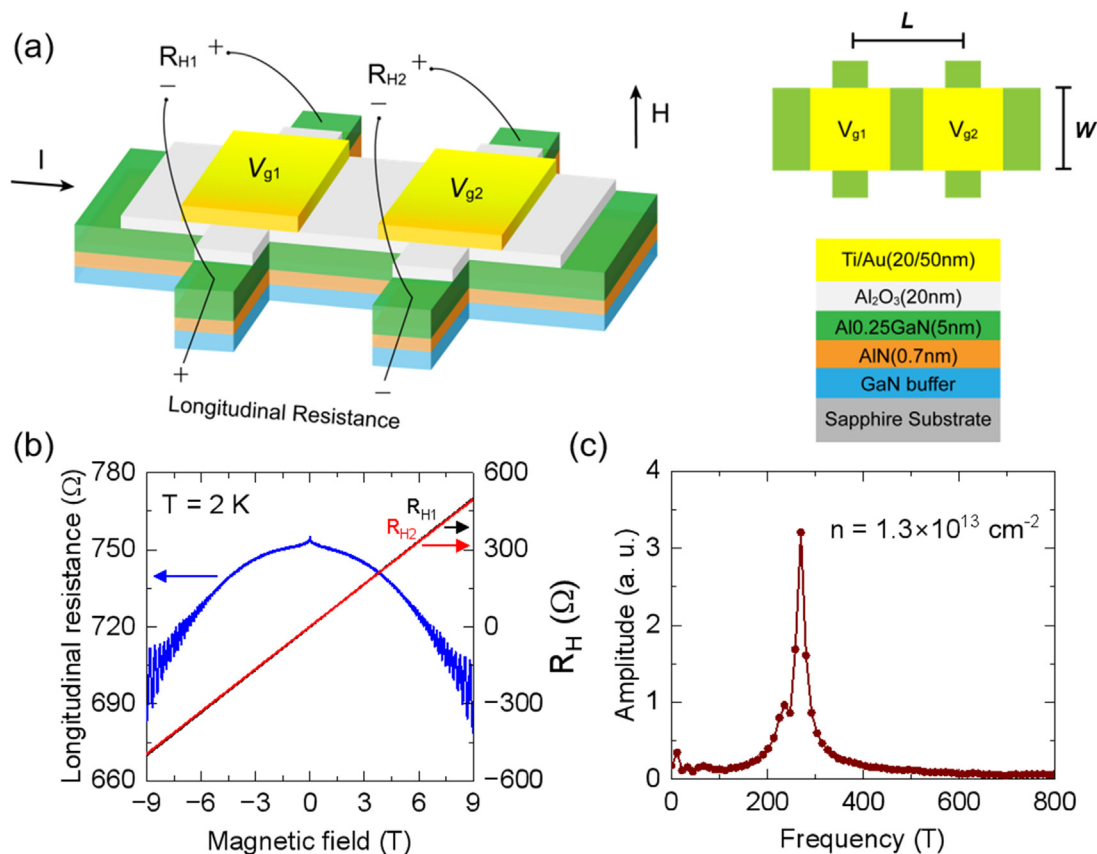


FIG. 1. (a) Schematic diagram of the 2DEG sample with two independent metal gate electrodes V_{g1} and V_{g2} . The film structure is shown in the right panel. (b) The longitudinal resistance and Hall resistances as a function of the magnetic field at $T = 2 \text{ K}$. (c) Fast Fourier transform (FFT) spectra of the data in (b).

Figure 2 displays the magnetic field dependence of the longitudinal resistance of the sample at several selected gating voltages. As shown in Fig. 1(a), two gating voltages, V_{g1} and V_{g2} , can be independently applied to the two sections. In Fig. 2(a), both V_{g1} and V_{g2} are simultaneously set to -6 V. The R_{xx} vs H curve exhibits a pronounced positive magnetoresistance, in contrast to the negative magnetoresistance under zero gating voltage.¹⁹ The Hall resistances of R_{H1} and R_{H2} increase at $V_{g1} = V_{g2} = -6$ V compared to zero bias, indicating electron concentration reduction in both gating regions. The gating effect also suppresses the SdH oscillation of the device, which may result from diminished quantum coherence of the 2DEG carriers under

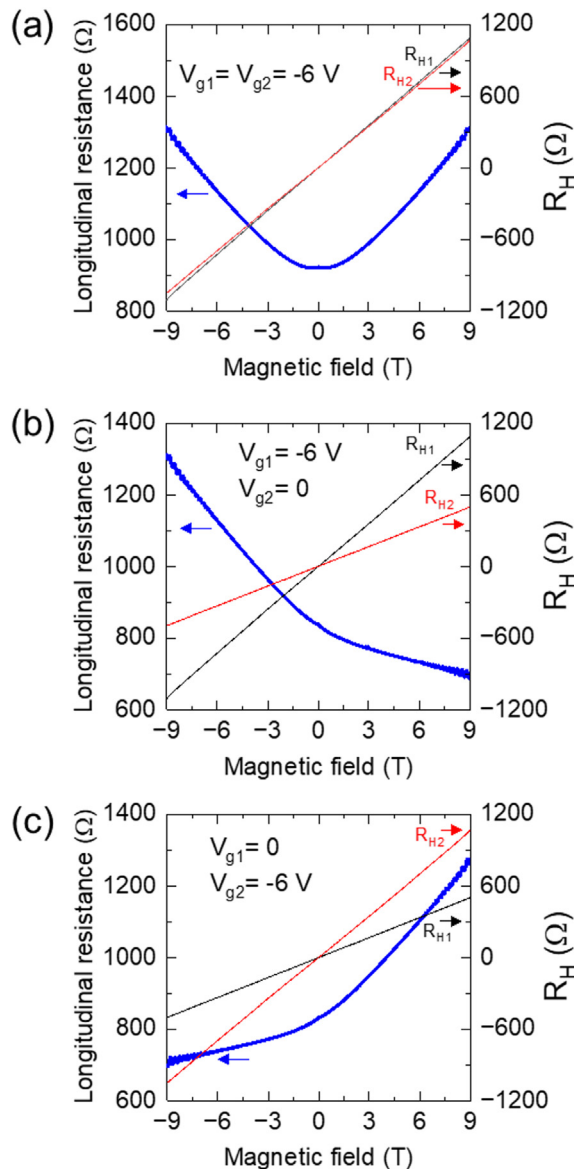


FIG. 2. (a)–(c) The magnetic-field-dependent longitudinal resistance and Hall resistances at different V_{g1} and V_{g2} gating voltages.

gating fields. In Fig. 2(b), V_{g1} is set to -6 V, while V_{g2} is set to 0 V, resulting in nonreciprocal magnetoresistance, as anticipated.^{21,22} The longitudinal resistance measures 1310Ω at $H = -9$ T and 689Ω at $H = 9$ T. This giant asymmetric signal can be reversed when we correspondingly set V_{g1} to 0 V and V_{g2} to -6 V, as shown in Fig. 2(c). The corresponding field-dependent R_{H1} and R_{H2} curves are presented in Figs. 2(b) and 2(c). Different Hall coefficients at the two sections can be realized by independently tuning the gating voltages of V_{g1} and V_{g2} .

Figure 3(a) shows the magnetic-field-dependent magnetoresistance of the device under various V_{g1} values, while V_{g2} is fixed at zero. Here, magnetoresistance MR is defined as $MR = \frac{[R_{xx}(H) - R_{xx}(0)]}{R_{xx}(0)} \times 100\%$, where $R_{xx}(H)$ and $R_{xx}(0)$ represent the longitudinal resistances at magnetic field H and at zero field, respectively. Notably, the magnetoresistance exceeds 70% at $V_{g1} = -7$ V and $H = -9$ T. The inset of Fig. 3(a) shows the gate-dependent carrier concentration in the left section [see Fig. 1(a)], derived from the Drude model. The electron concentration decreases linearly as V_{g1} is varied from 0 to -7 V, indicating the high quality of the Al_2O_3 dielectric layer. (Actually, the leakage current is less than 1 nA in our experiment.) Consequently, the increasing difference in Hall coefficients of the left and right sections monotonically enhances the asymmetric behavior. To demonstrate the effect of the odd longitudinal term of the resistance, the OMR data are presented in Fig. 3(c). The results demonstrate that a linear OMR phenomenon is obtained by applying V_{g1} and V_{g2} voltages, with tunable “off” and “on” states with a giant OMR value of $\sim 43\%$. Remarkably, this value surpasses those reported in conventional magnetic systems,^{1,2,6–8,28} highlighting the exceptional performance of our non-magnetic 2DEG platform. To further enhance the OMR effect, we fabricated Device 2 with identical parameters to Device 1, except for a 16% shorter channel length, aiming to reduce the intrinsic longitudinal resistance and thereby enhancing the Hall-asymmetric signal. The corresponding results are shown in Figs. 3(b) and 3(d). A notable enhancement in both magnetoresistance and OMR was achieved for Device 2. The OMR value reaches 60.5% under the same conditions ($T = 2$ K and $H = -9$ T), validating the effectiveness of enhancing OMR effects by strategically engineering the device.⁵

In fact, Onsager’s relation emphasizes the intrinsic resistivity ρ_{xx} (the proportionality coefficient that relates the local electric field E_x and the electric current density j_x) rather than resistance. It is worth noting that, experimentally, it is not the longitudinal resistivity ρ_{xx} but the longitudinal resistance R_{xx} that is measured. The latter is a non-local transport coefficient whose measurement involves four terminals. While $R_{xx} = \rho_{xx}$ in spatially uniform 2D devices, the two quantities can behave very differently in general. In particular, Onsager’s reciprocal relation is not expected to hold for R_{xx} in general, leading to $R_{xx}(H) \neq R_{xx}(-H)$ even in non-magnetic systems.

Since the above-mentioned analysis shows that the resistance rather than resistivity is measured, it is crucial to emphasize that the sign of the OMR obtained in our devices depends on the longitudinal voltage terminals used during the measurements.²² Figure 4 illustrates the magnetic field dependence of the longitudinal resistances R_{xx} and R'_{xx} , measured through the bottom and top voltage leads, respectively, as depicted in Fig. 4(a). From the results in Figs. 4(b) and 4(c), it can be concluded that $R_{xx}(H) \approx R'_{xx}(-H)$, which is consistent with the calculations from Kirchhoff’s circuit laws.^{5,21} Notably, the occurrence of OMR in our non-magnetic 2DEG devices does not violate the

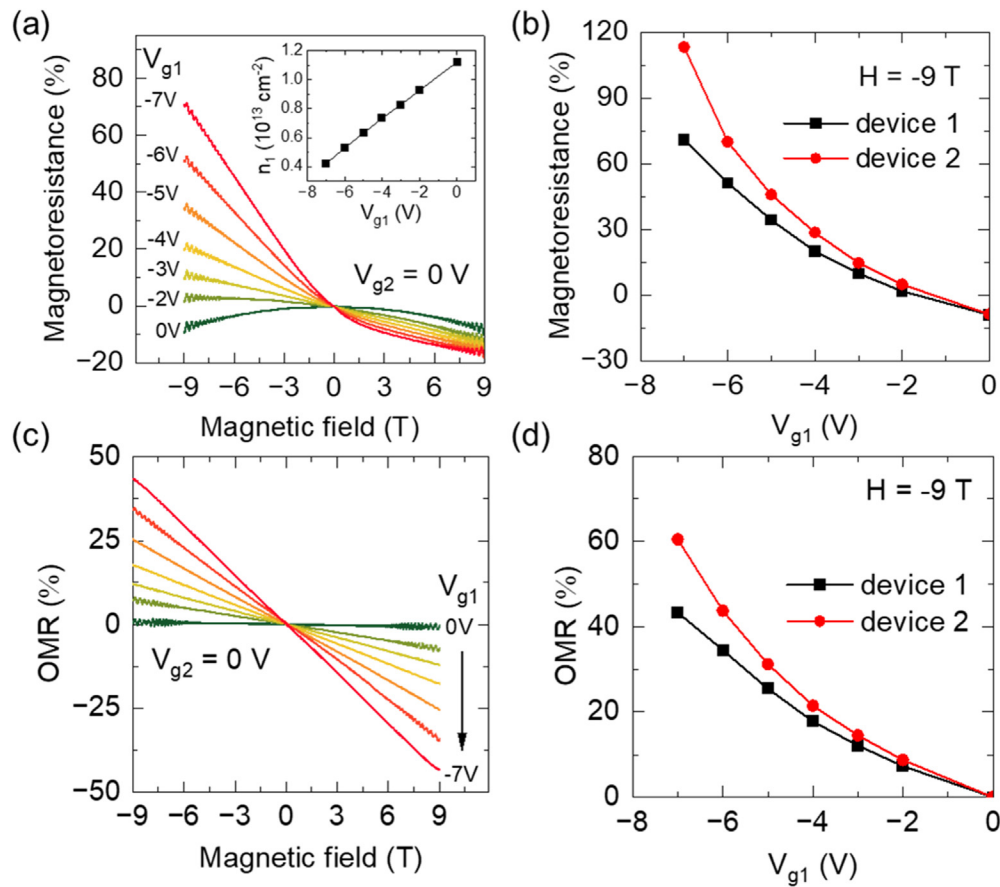


FIG. 3. (a) and (c) The magnetic-field-dependent magnetoresistance and the related OMR data of the device under different V_{g1} , while V_{g2} is fixed at zero. The inset of (a) shows the carrier concentration in the left gating area as a function of V_{g1} . (b) and (d) The comparison of the magnetoresistance and OMR at $H = -9$ T of the two devices with different channel lengths.

Onsager's reciprocity relation. The dual-gate control breaks the spatial symmetry along the current path, while the external magnetic field breaks time-reversal symmetry. Together, these effects enable the OMR effect. This mechanism mirrors that in magnetic systems, where

the apparent non-reciprocity similarly stems from the superposition of longitudinal resistance and local Hall resistance. If we define the longitudinal resistance of the device as $[R_{xx}(H) + R'_{xx}(-H)]/2$, the asymmetry disappears with any gating configurations as implied in

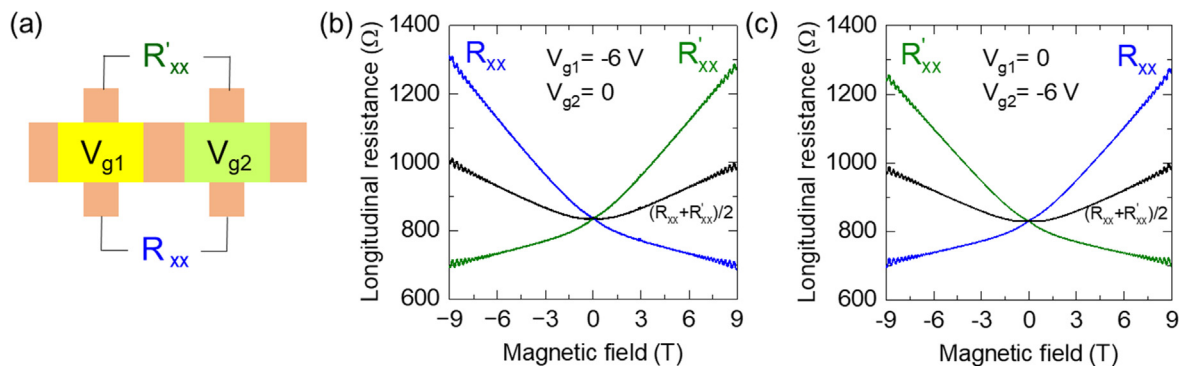


FIG. 4. (a) Schematic diagram of the longitudinal resistances R_{xx} and R'_{xx} for the measurement setup. (b) and (c) The magnetic field dependence of the longitudinal resistances R_{xx} , R'_{xx} , and $[R_{xx}(H) + R'_{xx}(-H)]/2$ at different applied gating voltages.

Figs. 4(b) and 4(c). Moreover, achieving a giant OMR in a non-magnetic system requires a Hall voltage variation significantly larger than the longitudinal voltage drop, as shown in our results. Therefore, 2DEG materials with engineered electrical gating represent excellent candidates for realizing giant OMR effects. The prototype device based on the 2DEG in AlGaIn/GaN heterostructures exhibits robust performance at low temperatures. For room-temperature applications, ultra-high-mobility 2D materials and their heterostructures are promising alternatives.^{29,30}

In summary, we have demonstrated a giant and electrically tunable odd-parity magnetoresistance effect in a non-magnetic AlGaIn/GaN 2DEG heterostructure. By leveraging spatially selective carrier density modulation using dual-gate control, we introduced a tailored Hall coefficient gradient along the current path, enabling a highly linear and reversible OMR response with a remarkable magnitude exceeding 60% at 2 K. Optimization of the device geometry, such as reducing the channel length, further amplifies the OMR by increasing the Hall contribution to the longitudinal resistance. The multi-gate control strategy and scalability of the design provide a promising route toward practical electronic device applications. It should be noted that the maximum OMR value reported here was measured under extreme conditions (9 T and 2 K), practical applications would require operation at higher temperatures and lower fields. In this context, high-mobility 2D materials (e.g., graphene³¹) may offer a more viable pathway for room-temperature OMR devices, whose OMR effect can be artificially manipulated at much higher temperatures.

This work was supported by the National Natural Science Foundation of China (No. 62304088), the National S&T Major Project of China (No. 2024ZD0301300), the Huai'an Natural Science Research Program (No. HABL202204), and the Jiangsu Universities Natural Science Foundation (No. 23KJB510002). C.W. was supported in part by the Research Grants Council of Hong Kong (GRF 17300724 and CRF C7012-21G) and the National Natural Science Foundation of China (Grant No. 12222416).

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Ting-Ting Wang: Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Writing – original draft (lead). **Ze-Pei Li:** Formal analysis (equal); Investigation (equal). **Chenjie Wang:** Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Writing – review & editing (equal). **Sining Dong:** Formal analysis (equal); Investigation (equal); Writing – original draft (equal). **Yong-Lei Wang:** Formal analysis (equal); Funding acquisition (equal); Supervision (equal); Writing – review & editing (equal).

DATA AVAILABILITY

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

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