High-performance broadband infrared (IR)/terahertz (THz) detection is crucial in many optoelectronic applications. However, the spectral response range of semiconductor-based photodetectors is limited by the bandgaps. This paper proposes a ratchet structure based on the GaAs/Al$_x$Ga$_{1-x}$As heterojunction, where the quasi-stationary hot hole distribution and intravalence band absorption from light or heavy hole states to the split-off band overcome the bandgap limit, ensuring an ultra-broadband photoreponse from near-IR to THz region (4 to 300 THz). The peak responsivity of the proposed structure can reach 7.3 A/W, which is five orders of magnitude higher than that of the existing broadband photon-type detector. Because of the ratchet effect, the proposed photodetector has a bias-tunable photoresponse characteristic and can operate in the photovoltaic mode with a broad photocurrent spectrum (18 to 300 THz). This work not only demonstrates a broadband photon-type THz/IR photodetector but also provides a method to study the light-responsive ratchet.

INTRODUCTION

In recent years, infrared (IR)/terahertz (THz) photodetectors have attracted great attention and have been intensively explored due to their diverse range of applications, including biomedical, astrophysics, national security, and next-generation communication systems (1–5). However, designing high-performance broadband IR/THz detectors has been challenging. Although notable improvements have been achieved in the recent decades, the existing IR/THz photodetectors still suffer from different drawbacks, limiting their practical application. The thermal detectors, such as a bolometer, Golay cells, and pyroelectric photodetector, represent highly developed broadband detectors, which have been commercially available (6). Still, high sensitivity and fast response cannot be achieved at the same time. Although the real-time imaging (with a frame rate > 24Hz) has already achieved for nearly all the thermal detectors, the modulation frequency is usually <100 Hz (7). The Schottky barrier diode–based THz direct photodetectors can realize submicrosecond response time. However, the limited response frequency range (<2 THz) is the main drawback to the wider application of these photodetectors (8). Therefore, further extension of the frequency coverage and array integration of Schottky diodes are highly desired. A field-effect transistor–based photodetector is compatible with standard silicon microelectronics processing technology and could be a promising candidate for large-scale imaging arrays (7, 9), but its narrow response bandwidth represents an obstacle for its wide application.

Photon-type detectors exhibit an adjustable response range, a good signal-to-noise performance, and very fast response (6). Highly developed HgCdTe detectors have been widely used in the IR region, but their spectral range can be difficultly extended to the THz region. Quantum-well photodetectors (QWPs) have been proven to be excellent photon-type IR/THz photodetectors, benefiting from the fast response speed, high sensitivity, and flexible and adjustable photon-response range (10–12). However, because of the limitation in the selection rule of intersubband transition (ISBT), the n-type QWP usually requires using an optical coupling structure (13–15). Although the narrowband detection characteristic makes the QWP optical filter convenient for certain applications, their spectrum coverage has been limited. The homojunction and heterojunction interface work function internal photoemission (HIWIP and HEIWIP, respectively) photodetectors have been considered competitive broadband IR/THz photodetectors because of their normal incidence response mechanism, wide spectrum response coverage, and tailorable cutoff frequency (16, 17). Unfortunately, the low activation energy (~10 meV) of the IWIP results in a large dark current and requires extremely low temperature (~4 K) operation conditions (18). Another alternative could be a quantum dot photodetector, which can realize THz detection, normal-incidence response, and high-temperature operation. However, the reliability and repeatability of the quantum dot material growth represent still a great challenge (19). The optical pumped hot hole effect detector (OPHED) is based on the hot-cold hole energy transfer mechanism that can overcome the bandgap spectral limitation and realize an ultra-broadband IR/THz detection (20). This type of detection mechanism enables a designable detection wavelength by adjusting the potential barrier while simultaneously suppressing the dark current and noise (21). However, the external optical excitation-dependent hot hole injection is the prerequisite for THz detection, which greatly increases the OPHED complexity. Moreover, the related studies have reported a responsibility of only a few microamperes per watt, which indicates the need for further optimization (20).

Ratchets are nonequilibrium systems that break spatial inversion symmetry, which can be realized in many systems (22). Producing

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directional motion of microparticles by using a time-varying input of nondirectional or random perturbations, such as radiation, heat, or applied AC fields, without using a bias is the typical feature of the ratchet effect (23). This concept originates from the cognitive process of symmetry laws and the second law of thermodynamics. Extensive research has been conducted in the fields of photovoltaics and molecular motors since it came into the 21st century (24–26). Radiation detection (sensing) is one of the main suggested applications where incident radiation is rectified in ratchets to produce currents (27–30). The ability to work under the zero bias and the bias-adjustable photoresponse range make ratchet photodetectors to have great potential in the field of high-temperature and broadband detection. The mature material growth technology and a large bandgap difference between GaAs and AlAs provide many possibilities for constructing unique type ratchet-like potential by band engineering to realize the broadband and THz photon-response (31–33).

In this work, a broadband photon-type detector based on the GaAs/Al\textsubscript{x}Ga\textsubscript{1−x}As ratchet structure is proposed. The proposed photodetector allows normal incidence excitation, thus bypassing the need for a grating coupler usually required in the ISBT-based detectors. An ultrabroadband photodetector (4 to 300 THz) covers a much wider range than the other photon-type detectors. The THz response achieved by the electrically pumped hot hole injection and the establishment of a quasi-stationary hot hole distribution breaks the spectral response limit. Moreover, an evident photocurrent can be obtained even at the zero-bias voltage, and the response spectra exhibit strong bias-dependent characteristics. The peak responsivity of the proposed photodetector is five orders of magnitude higher than that of the OPHED. In addition, the ratchet photodetector exhibits pronounced rectification behavior at a temperature below 77 K due to the ratchet effect. The dark current of the detector is also much lower than the existing photon-type detectors due to the high inherent barrier design, which makes it possible to improve the operating temperature.

RESULTS
Device structure
The schematic structure of the ratchet photodetector device is displayed in Fig. 1A (see Materials and Methods and the Supplementary Materials for the wafer details). All the p-type GaAs are doped to a Be concentration of \(1 \times 10^{19} \text{ cm}^{-3}\). The valance band diagram of the ratchet photodetector under zero bias is shown in Fig. 1B. The basic detection cell is presented in the dashed box, and it represents a four-layer structure consisting of the injector layer, graded barrier layer, absorber layer, and constant barrier layer. The barrier shape is an aluminum component \((x)\) of the Al\textsubscript{x}Ga\textsubscript{1−x}As. The bottom contact layer serves as an injector layer of the first period of the ratchet photodetector, which causes the first injector to be thicker than the other periods. The internal work functions \((\Delta \Phi)\) of the barriers in the detector structure are calculated as 67 and 120 meV according to the high-density (HD) theory (see the Supplementary Figure 1. Device structure of the ratchet photodetector. (A) Mesa structure of the ratchet photodetector device. (B) Valance band (VB) diagram of ratchet photodetector, the basic detection cell is displayed in the dashed box that is a four-layer structure consists of injector layer, graded barrier, absorber layer, and constant barrier. (C) The photoluminescence (PL) spectrum of the quantum ratchet photodetector at room temperature. e1 → VB and e2 → VB correspond to the transitions from the first and second subbands in conduction band to the valence band, respectively. e1 → A is the transition from the first subbands in conduction band to the acceptor impurity band. a.u., arbitrary units. (D) Schematic diagram of the THz/IR photoresponse in the ratchet structure: The IR or THz photon absorption is based on the ratchet-like valance band and occurs in the highly doped GaAs layers (injector and absorber).
Materials for the work function calculation of the GaAs/AlGaAs heterojunction \((16, 34)\), which indicates the cutoff frequency of about 16 THz. As shown in Fig. 1C, the photoluminescence (PL) spectrum of the ratchet photodetector at room temperature includes broadband radiative recombination PL peaks. Because the p-type GaAs region is heavily doped \((1 \times 10^{19} \text{ cm}^{-3})\), there are no discrete quantum states in the valence band, and holes form a three-dimensional distribution in p-GaAs. In the conduction band, there is a subband separation. The peaks at 920, 900, 877, and 735 nm are from the transition in the highly doped GaAs layer. The calculation result of the quantum-well band structure \((12, 17)\) shows that the peaks at 900 and 877 nm correspond to the transitions from the first and second subbands in conduction band to the valence band, respectively. The peak at 920 nm is due to the transition from the first subbands in conduction to the acceptor impurity band. The peaks at 864, 847, and 780 nm are caused by the interband transitions from Al\(_x\)Ga\(_{1-x}\)As graded barrier, corresponding to Al compositions of 0.13, 0.05, and 0.01, respectively. The peak at 800 nm is mainly caused by the constant barrier \((\text{Al}_0.1\text{Ga}_{0.9}\text{As})\). The peak at 735 nm is due to the transition from the conduction to the split-off (SO) band.

The schematic diagram of the THz/IR photoresponse in the ratchet photodetector is shown in Fig. 1D. The IR absorption is based on the ratchet-like valance band and occurs in the highly doped GaAs layers (i.e., injector and absorber) followed by internal photoemission. The emitted carriers are swept out and collected by the electrode. The IR absorption can be achieved under low bias voltage because the photon energy is greater than the barrier energy. On the contrary, the THz energy is much smaller than the barrier energy. The THz response implies breaking the bandgap limit. This complex mechanism involves a hot-cold hole energy transfer process and will be discussed in detail in the following.

**Bias-tunable THz/IR photoresponse**

The responsivity of the photodetector as a function of the bias voltage is presented in Fig. 2A, where it can be seen that the peak responsivity is 7.3 A/W, which is about five orders of magnitude higher than that of the OPHED; for the responsivity calibration method, see the Supplementary Materials. The near-IR (NIR; 80 to 300 THz) photoresponse mechanism is caused by the SO band absorption (SOA) and consists of three main steps: (i) photoabsorption that excites the holes from the highly doped emitters (i.e., injector and absorber), where a direct transition occurs from light or heavy hole band to the SO band; (ii) scattering-assisted escape of the photoexcited carriers; and (iii) collection of the escaped carriers \((35, 36)\). The response mechanism of the mid-IR (MIR) and far-IR (FIR) photons (16 to 80 THz) is primarily caused by the free carrier absorption (FCA)–based internal photoemission. In this range, the injector behaves the same as the absorber, and the detector operates as a HEIWIP photodetector \((34)\); the detector can respond to the MIR or FIR photons, and the cutoff frequency is typically defined by the spectral rule: \(\nu_c = \Delta E_s / h\), where \(\Delta E_s\) is the internal interface work function \((20)\). However, the permanent barrier of the absorber–graded barrier junction or the injector–constant barrier junction cannot be overcome; thus, it is difficult to achieve the cutoff frequency below 16 THz. The cutoff frequency is selected when the spectra signal reaches the noise level (refer to 1% of the peak signal in this work).

However, the cutoff frequency of the photodetector under negative bias (with the top contact being grounded) can be as low as 4 THz, which breaks the limit of spectral response rule in semiconductor photoelectronic devices \((\Delta E_s = 67 \text{ meV})\). The extension of the cutoff frequency can be attributed to the hot-cold hole energy transfer mechanism and barrier bending caused by the electric field \((20, 21)\). The band structures at the equilibrium and negative bias are calculated using a two-dimensional Poisson solver and shown in Fig. 2B. As shown in Fig. 2B, with the increase of negative bias, the whole active region of the device shows a band incline. The apparent incline and bending of the graded barrier in Fig. 2B indicate that the electric field is first applied to the graded barrier. When the voltage changes from 0 to \(-2 \text{ V}\), \(\Delta I-G\) changes from 120 to 45 meV. The band structures for the one-single period at 0, \(-1\), and \(-2 \text{ V}\) are shown in Fig. 2 (C to E), respectively. At the equilibrium, the high barrier inside the device will block all the THz-photocarriers, which determines that there will be no THz response, as shown in Fig. 2C. When the bias increases to \(-1 \text{ V}\), as shown in Fig. 2D, a large number of holes can be injected into the absorber because the graded barrier is greatly tilted and bent. The holes injected into the absorber are hot holes because they have excess energy of more than 120 meV, which is higher compared to the indigenous cold holes in the absorber \((37, 38)\).

The energy transfer mechanism between the hot and cold holes occurs during the relaxation process of the hot holes. According to the hot hole relaxation theory and experimental results \((39)\), a hot hole first releases an optical phonon, and then, the hot holes with the excess energy inelastic scatter with the cold holes below the hole quasi-Fermi level (HQF), rapidly reestablishing a thermalized quasi-stationary hot hole distribution \((20, 39)\). It should be noted that the quasi-stationary hot hole distribution is a dynamic distribution after the scattering-caused energy transfer, which is different from the traditional HQF. In addition, the duration (lifetime) of this quasi-static distribution is on the order of tens of picoseconds \((40)\). This distribution can reduce the activation energy of carriers in the absorber so that the THz response can be realized, as shown in Fig. 2E. It is not difficult to find that THz detection based on the hot hole energy transfer requires an energy difference \((8E_b)\) between the graded barrier and constant barrier, which has been confirmed by a previous reported work \((21)\). The holes that crossing the graded barriers are all hot holes because of their excess energy compared to the cold holes below the HQF. These thermal holes can be caused by external field injection, thermal excitation, and high-frequency photoexcitation. The energy transfer mechanism is considered to be the main cause of the THz response under negative voltages. This mechanism has been studied theoretically and supported by ultrafast IR spectroscopy and hot carrier spectroscopy \((39-42)\). A similar mechanism was interpreted as the hot-cold hole energy transfer in the OPHED \((20)\), where the hot holes are caused by the optical pumping followed by the electric field injection.

In addition, the holes that surmounting the constant barrier are also hot holes relative to the low-energy holes in the injector. Thus, the energy transfer mechanism that occurs in the absorber is also likely to occur in the injector. According to the traditional HD theory, the internal work function of the injector–graded barrier \((1-I-G)\) interface is only about 15 meV, and it can be reduced due to the hot-cold hole energy transfer. Moreover, according to the result in Fig. 2F, \(\Delta I-G\) decreases with the negative bias. Lower work function and barrier potential increase the probability of THz-photocarriers crossing the graded barrier, which can contribute to the THz response. However, the proportion of THz absorption in the absorber and injector cannot be precisely determined in this work.
work, and further work can be performed using a single-period structure for accurate verification.

To further clarify the hot-cold hole energy transfer mechanism, the activation energy of the detector (Δ) is obtained by the Arrhenius fitting based on the current-voltage-temperature (I–V–T) data (43), as shown in Fig. 2G. As shown in Fig. 2H, the activation energy agrees well with the cutoff energy defined as $h\nu_c$, indicating that the THz response of the ratchet detector is determined by Δ rather than the calculated internal work function ($\Delta_B$ or $\Delta_{I-G}$). The dependence of $\Delta$, $\Delta_B$, and $\Delta_{I-G}$ on the bias voltage is presented in Fig. 2 (F and H), where it can be seen that $\Delta$ is almost equal to $\Delta_B$ under zero bias. As the bias voltage decreases from 0 to −1 V, $\Delta_B$ is reduced only by 5 meV and $\Delta_{I-G}$ decrease from 120 to 67 meV, while $\Delta$ is reduced greatly by 50 meV. At −1 V, $\Delta$ is only 16.1 meV, shifting the cutoff frequency to 4 THz and breaking the limit of $\Delta_B$ and $\Delta_{I-G}$. It should be noted that in the previous studies on THz-HIWIP and THz-HEWIP, $\Delta_B$ or $\Delta_{I-G}$ was relatively low and agreed well with $\Delta$, and the corresponding mole fraction of Al in the GaAs/AlGaAs heterojunction was generally lower than 2% (16, 18, 34). In contrast, a higher Al fraction could be used in a ratchet photodetector. These results indirectly prove the mechanism of the hot-cold hole energy transfer and reveal that the hole energy in the quasi-stationary hot hole distribution is higher than the cold holes in heavily doped GaAs regions. From this point of view, the extracted activation energy data can accurately describe the internal work function inside the detector.

Because the device works at extremely low temperatures of about 4.2 K, the photoresponse of the detector can also be caused by the thermal bolometric artifacts. To clarify the photoresponse mechanism further, experiments were conducted, and the highest chopping frequency could reach 3.6 kHz. The oscilloscope waveforms at different chopping frequencies in the frequency range of 15 to 150 THz (KRS-5 window for cryostat) are presented in Fig. 3A.
showed that as the chopping frequency increased, the response amplitude of the detector remained almost unchanged. The device showed stable and repeatable photoresponse to varying optical signals over a wide frequency range of up to 3.6 kHz at different bias voltages, as shown in Fig. 3B. The results in the THz range (<20 THz) are presented in Fig. 3 (C and D), where it can be seen that the photoresponse in the detector was also chopping frequency independent. These behaviors are contrary to the response characteristics of a bolometric detector, so the influence of the thermal bolometric artefacts in this situation can be eliminated. Thus, the THz/IR response in a ratchet detector originates from the photoelectric effect.

**Dark current and ratchet effect**

The dark currents of a ratchet photodetector at different temperatures are shown in Fig. 4A. The $I-V$ curves show rectification characteristics because of the asymmetry of the ratchet structure, which can be explained by the tilting ratchet effect (27).

The asymmetry of the $I-V$ curve below 40 K is due to the directional flow of thermally generated carriers driven by the ratchet potential, resulting in a net dark current in the device at zero bias. This can be regarded as a thermally excited ratchet effect in the device. When the temperature is higher than 40 K, the thermal excitation of the device becomes very strong, and the asymmetric effect caused by the ratchet barrier is shielded. This phenomenon has also been observed in the QWP with an asymmetric barrier (44), which has similar temperature-dependent results. The dark currents of the ratchet photodetector, QWP (13, 45), and HIWIP (16) at the temperature around the liquid helium temperature are presented in Fig. 4B, where it can be seen that the dark current of the quantum ratchet photodetector was much lower than those of the HIWIP and QWP in a large electric field range. This could be attributed to the higher inherent barrier in the ratchet photodetector. The lowest barrier energy in the ratchet structure was about 67 meV (constant barrier), which was much higher than those of the HIWIPs and QWPs. Therefore, in the ratchet photodetector, most of the thermal- and field-emitted carriers were blocked by the barrier even under a large electric field.

The ratchet-like potential barrier could not only result in a low dark current but also produce an evident ratchet current even under the zero bias if the detector was illuminated by the THz or IR radiation. As shown in Fig. 4C, under the zero bias, the IR photons stochastically changed the momentum and energy of the holes in both the injector and the absorber. The occurred absorption includes the FCA and SOA (35, 36). Then, the asymmetry of the repeated unit of the barrier potential biased the holes’ motion to the left due to the
asymmetric relaxation (25, 26). This phenomenon has been known as the light-induced ratchet effect, which can be considered a photovoltaic mechanism (26). Therefore, the ratchet photodetector can be regarded as a broadband photovoltaic detector. The responsivity of the ratchet photodetector under the zero bias is displayed in Fig. 4D, where a wide response range of 18 to 300 THz and a peak responsivity of 22.1 mA/W at 30 THz can be observed.

In the THz- or IR-based detection applications, a high value of responsivity is desirable, but that is not the only requirement. Noise also affects the performance of devices. Therefore, the noise equivalent power (NEP), which has been the most widely used figure of merit for the THz and IR photodetectors, should be determined. The noise theory, experimental results, and the transport mechanism of the proposed photodetector are given in the Supplementary Materials. The calculated optimal NEP value is about 3.5 pWHz$^{-1/2}$ at 18 THz under a bias of $-2.6$ V, and the corresponding specific detectivity ($D^*$) can reach $2.9 \times 10^{10}$ Jones. The reason why such a small NEP can be maintained at a large voltage is that a high potential barrier in the ratchet structure reduces the dark current of a device.

**DISCUSSION**

In this study, we demonstrated an ultrabroadband THz/IR ratchet photodetector. The proposed ratchet photodetector had potential superiorities compared to the existing photon-type THz photodetectors. The comparison of the proposed ratchet detector and the state-of-the-art photon-type IR/THz detectors is given in Table 1. The main advantages of the quantum ratchet photodetector are an ultrabroadband photon-type response and that it can allow normal incidence absorption without adding an extra optical coupler required for the ISBT-based detector, such as n-type quantum-well IR photodetector or quantum cascade detector (QCD) devices. In the proposed ratchet structure, the dark currents are suppressed by a relatively high potential barrier, which enables the photodetector to work within a wide bias range and at higher temperatures. In addition, an inherent short carrier lifetime of the proposed detector makes it able to operate at high speed. All the mentioned features make the proposed ratchet photodetector a promising solution for broadband detection and up-conversion pixel-less imaging applications (17).

Further, the proposed photodetector exhibits a bias-tunable behavior for the THz photoresponse, which provides more solutions for specific applications, such as search tracking, target recognition, THz/IR biophysics (46, 47), and research on the development of THz/IR spectrometers. Furthermore, because of the multiperiod design and bias-tunable hot hole injection in the ratchet structure, the peak responsivity of the quantum ratchet photodetector can reach 7.3 A/W, which is about five orders of magnitude higher than that of the OPHED. The electrically pumped THz photoresponse in the proposed photodetector also eliminates the requirement for the external excitation source in the OPHED, thus making the photodetector more compact.

The results presented in this work prove that the proposed ratchet structure has great application potential in the field of THz and IR photon detection. The photoresponse mechanism at the
zero bias in the proposed ratchet photodetector can be considered as a photovoltaic scheme (25, 26), which also shows a broadband photoresponse. Thus, this work not only demonstrates a broadband bias-tunable THz/IR photodetector but also provides a method to study the quantum ratchet or light-responsive ratchet.

**MATERIALS AND METHODS**

**Wafer details and fabrication**

The active region of the quantum ratchet photodetector consisted of 16 basic ratchet detection cells directly grown by the molecular beam epitaxy on a 625-μm-thick semi-insulating GaAs substrate. The basic ratchet detection cell consisted of a 20-nm GaAs injector layer highly doped with Be (doping concentration, 1 × 10^{19} \text{ cm}^{-3}), an 80-nm Al_{x}Ga_{1-x}As graded barrier with x linearly varying from 0 (bottom) to 0.2 (top), a 20-nm GaAs absorber layer highly doped with Be (doping concentration, 1 × 10^{19} \text{ cm}^{-3}), and a constant Al_{x}Ga_{1-x}As barrier with the Al fraction of 0.1 and thickness of 80 nm. The active regions were sandwiched between two p-type GaAs ohmic contact layers doped with Be acceptor to the doping concentration of 1 × 10^{19} \text{ cm}^{-3}. The doping levels of the injector and absorber were selected to achieve high FCA while avoiding direct transitions from the heavy to light hole band. The heavy p-type doping made the Fermi level go inside of the valence band by about 17 meV. The samples were processed using standard photolithographic techniques. Square mesa structures with areas of 400 μm by 400 μm, 600 μm by 600 μm, and 1000 μm by 1000 μm were fabricated using wet-chemical etching. The top electrical connection was a narrow ring contact with a width of 70 μm, which was formed by deposition of the Ti/Pt/Au through the electron beam evaporation. The bottom common electrode was also a p-contact metal obtained by the electron beam evaporation of Ti/Pt/Au.

**Measurement details**

The samples were mounted on 14 pin packages for electrical and optical measurements. All measurements were performed at low temperatures. The photocurrent spectra at 4 K and different bias voltages (see the Supplementary Materials) were measured using a Fourier transform IR (FTIR) spectrometer (Bruker VERTEX 80 IFS 66 v/s). The responsivities of the photodetector at different bias voltages were acquired using a calibrated blackbody (Infrared Systems Development Corporation IR-564/301), a low-noise current preamplifier (Model SR570), and a lock-in amplifier (Model 3500). The radiation beam illuminated on the device from the globar lamp was passed through KRS-5 or quartz windows, respectively. The radiation beam illuminated on the device from the globar lamp in the FTIR spectrometer was a circular spot with 8-mm diameter. The aperture diameter of the blackbody was set below 0.4 inches, which was regarded as a point light source emitting divergent light illuminating on the device.

**SUPPLEMENTARY MATERIALS**

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Foundation (2020 M680458), and Open Project funded by Key Laboratory of Artificial Structures and Quantum Control (2020-03). **Author contributions:** P.B., W.C., Y.Z. and Z.Z. conceived the experiment and designed the device structure. P.B. fabricated the photodetector devices and carried out the electrical and optical experiment. P.B., X.L., Y.Z., N.Y., and W.C. contributed to the data analysis and figures. X.L., X.B., S.H., Z.F., D.S., Z.T., H.L., and J.C. contributed to all the measurement of the ratchet photodetector. L.L. and E.H.L. grew the samples using molecular beam epitaxy. P.B. wrote the main manuscript text. X.L., W.C., Y.Z., N.Y., W.S., Y.X., and Z.Z. reviewed the manuscript. All authors discussed the results and contributed to the manuscript. **Competing interests:** The authors declare that they have no competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials.

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