Development of highly efficient and stable lateral organic circularly polarized light photodetector is a fundamental prerequisite for realization of circularly polarized light integrated applications. However, chiral semiconductors with helical structure are usually found with intrinsically low field-effect mobilities, which becomes a bottleneck for high-performance and multi-wavelength circularly polarized light detection. To address this problem, here we demonstrate a novel strategy to fabricate multi-wavelength circularly polarized light photodetector based on the donor-acceptor heterojunction, where efficient exciton separation enables chiral acceptor layer to provide differentiated concentration of holes to the channel of organic field-effect transistors. Benefitting from the low defect density at the semiconductor/dielectric interface, the photodetectors exhibit excellent stability, enabling current roll-off of about 3~4% over 500 cycles. The photocurrent dissymmetry value and responsivity for circularly polarized light photodetector in air are 0.24 and 0.28 A W$^{-1}$, respectively. We further demonstrate circularly polarized light communication based on a real-time circularly polarized light detector by decoding the light signal. As the proof-of-concept, the results hold the promise of large-scale circularly polarized light integrated photonic applications.
Circularly polarized light (CPL) carrying photons with spin angular momentum has attracted a wide range of interests for its practical applications in circularly polarized ellipsometric tomography, optical communication of spin information, quantum-based optical calculation, biology and medicine, etc.\textsuperscript{1–3}. Chiral optoelectronics is a key technology for quantum information and encryption by using the photonic properties of the particular chiral molecules or structures. In order to realize miniaturization and integrated CPL detecting application without using conventional waveplates, there have been increasing demands for optoelectronic devices to detect CPL\textsuperscript{4–7}. Hence, organic field-effect transistors (OFETs), as conventional optoelectronic devices\textsuperscript{8–14}, provide one of the effective and cutting-edge solutions to convert the direction and intensity of the CPL into sensitive electric signal.

So far, many kinds of chiral materials, including chiral organic materials, chiral perovskite (1D, 2D or quasi-2D), and metal-oxides hetero-chiral structures, have been applied in CPL photodetectors to distinguish the polarized states (Supplementary Tables 1–3)\textsuperscript{15–40}. Among them, chiral organic semiconductors combine high optical rotary power with strong circular dichroism (CD), making them extremely promising as building blocks for CPL photodetector\textsuperscript{15–25}. Typical chiral molecular materials in CPL detectors are not only responsible for chiral light absorption but also contribute to charge transport property. The fundamental issue is that the chiroptical response of organic semiconductors requires intrinsic high-level helical structures, which results in low or even no field-effect mobility owing to the asymmetry of the molecular packing. Thus, most of the chiral materials exhibit mobility on the magnitude of $10^{-5}$–$10^{-3}$ cm$^2$V$^{-1}$s$^{-1}$ (Supplementary Table 4)\textsuperscript{15,16,19,22,23}, which severely restrains the performance of CPL photodetectors such as low photocurrent dissymmetry factor $g_{ph}$. Most of the $g_{ph}$ of organic CPL detectors based on chiral organic molecules are below 0.1, which hinders their further integration and application. In addition to that, almost all the reported FETs based CPL photodetectors could only work in vacuum or under nitrogen. The instability of organic semiconductors and the existence of semiconductor/dielectric interfacial defects have limited the durability of these devices\textsuperscript{41}.

In order to fundamentally address these issues, there are two strategies: (1) the optimization of the chiral materials or structures and (2) the architecture design of the photodetector. Herein, we propose an architecture design strategy by employing the chiral molecules without FET behavior is inserted between donor semiconductors and source/drain (S/D) electrodes. The geometry is designed following two motivations: (1) The exciton dissociation at the interface of donor-acceptor junction after CP selective absorption. The holes are injected into the p-type semiconductor layer which forms a photoinduction electric field to enhance the charge transport property of the semiconductor. (2) The semiconductors/dielectric layer interfacial defects are suppressed without nonconducting chiral acceptor as buffer layer at the interfaces, which reduces the current degradation of the device. Hence, highly stable in-situ CPL photodetectors are achieved based on the heterojunction top-gate bottom-contact (TGBC) photo FET. Especially, by choosing proper donor-acceptor material pairs, multi-wavelength detection can be realized by the structure demonstrated here. The dissymmetry value $g_{ph}$ of the CPL photodetectors is up to ±0.24 under 556 nm light illumination in air.

**Results**

**Fabrication and properties of CPL photodetector based on heterojunctions.** For high chiroptical property, we introduce chiral multiple helicene $C_3$-symmetric triple helicene based on N-annulated triperylenne hexaimide, namely NTPH\textsuperscript{12,32} as, the core chiral active layer in the CPL detector. The pair of enantiomers NTPH-P(P,P,P) (1-P) and NTPH-P(M,M,M) (1-M) (Fig. 1a) exhibits mirror CD response with the dissymmetry factor $g_{abs}$ around ±1.6×10$^{-3}$ and more than one impressive Cotton effects with multiplet in the visible region (Fig. 1b and Supplementary Figs. 1–3). The $g_{abs}$ spectra of the spin-coated films of 1-P and 1-M demonstrate three equal and opposite sharp peaks at 414 nm, 489 nm and 551 nm. Although the enantiomerically pure chiral molecules exhibit fairly good chiral activities in the absorption, the charge transport property of this N-type material based OFET is insufficient (Supplementary Figs. 4a and 5).

In order to realize efficient excitation separation to enhance CPL photocurrent, we employed the bilayer structure of donor-acceptor junction with chiral active layer inserted between high mobility semiconductor and S/D electrodes as shown in Fig. 1a (Supplementary Note 1, Supplementary Figs. 6, 7). 2,6-diphenylnaphthalene (DPA) was selected as the organic semiconductor layer owing to the high charge carrier mobility, easy preparation process and matching absorption spectrum (Supplementary Notes 2–3 and Supplementary Fig. 4)\textsuperscript{33,44}. To ensure sufficient absorption by the chiral active layer (Supplementary Fig. 8), the wavelength of the laser was selected at 556 nm. From the transfer curves of the photodetector based on NTPH-P/DPA crystal shown in Fig. 1c, the mobility, threshold voltage and the on/off ratio of the crystal-based photo FETs are around 1.1 cm$^2$V$^{-1}$s$^{-1}$, −20 V and 1×10$^5$, respectively, which are superior to their thin film counterparts (Supplementary Figs. 9–10). Although the introduction of the chiral layer has a slight effect on the contact resistance and properties of the devices, the charge transport properties are still the best in existing reports based on chiral organic system\textsuperscript{15,16,19,22,23} (Supplementary Fig. 11, Supplementary Table 5 and Supplementary Note 4). The crystal-based and film-based detectors exhibit outstanding stability with only 4% (Fig. 1d) and 30% (Supplementary Fig. 12b) on-state current degradation after 500 cycles in dark, respectively, while 130% and 137% (Supplementary Fig. 13b, f) roll-off are observed in the bottom-gate top-contact (BGTC) OFETs based on DPA crystal and film (Supplementary Fig. 14), respectively (Supplementary Table 6, Supplementary Fig. 15 and Supplementary Note 3). Moreover, under the illumination of 556 nm, the on-state current degradation of the single crystal DPA based detector is only 3% (Fig. 1f), further confirming the stability of TGBC DPA crystal-based photo FETs. The impressive stability in air could be attributed to the excellent quality of semiconductor/dielectric interface (Supplementary Fig. 16b), which is the prerequisite of the in-suit CPL detection. The optical switch of 1-P/DPA crystal-based photo FET under 556 nm light illumination is shown in Fig. 1f with the photosresponse up to 10$^2$ at intensity of 84.88 mW cm$^{-2}$. The highly stable device performance and obvious photosresponse provide the possibility for further application in real-time information transmission.

The properties of the photo FETs during exposure to left-handed CPL (LCPL) and right-handed CPL (RCPL) illumination are shown in Fig. 2 and Supplementary Figs. 17–19. Photo FETs show distinct photocurrent signal under the illumination of CPL in different polarized directions. From the transfer characteristics (Fig. 2a, Supplementary Fig. 17c), the current increase of 1-P/DPA based photo FETs under RCPL irradiation is higher than that under LCPL irradiation. In contrast, opposite phenomenon is observed for the 1-M/DPA based photo FETs, where higher photocurrent is obtained under the illumination of LCPL (Fig. 2c,
Mechanism of the CPL photodetector. To further probe the working mechanism of the detector, the fluorescence lifetime and scanning kelvin probe microscopy (SKPM) measurements are performed to understand the process of charge transfer. The fluorescence lifetime ($\tau$) of DPA crystals on different substrates is tested with the excitation wavelength of 405 nm (Fig. 3e). The results show that the $\tau$ of DPA crystals on chiral molecule film is significantly reduced compared with that of DPA crystals on silica. In order to further explore the constraints of dissymmetry factor $g_{ph}$, we adjusted the light intensity and the thickness of chiral active layer. Factor $g_{ph}$ can be regulated by the light intensity of the laser as shown in Fig. 3b, c. With the increase of the intensity, the photocurrent goes up by an order of magnitude, and the factor $g_{ph}$ is approximately linearly related to light intensity at the chosen intensity range. In addition, the CPL absorption is highly related to the absorbance of the chiral molecule and the layer thickness, as evidenced by the ellipticity spectra of NTPH-P films with different thickness in Supplementary Fig. 23. As expected, positive correlation between chiral material thickness and $g_{ph}$ in the test range is detected (Fig. 3d).

**Fig. 1 Architecture and device characteristics of the photodetector.** a Blayer donor-acceptor heterojunction organic photodetector adopting a device configuration of self-encapsulated bottom-contact top-gate FET in which the chiral active layer and the organic semiconductor layer are NTPH-P thin film and DPA crystal, respectively. The molecular structures of the two chiral forms of the NTPH-P are shown on the right side. b $g_{abs}$ spectrum of 1-P and 1-M thin films on quartz substrates. c Transfer characteristics (recorded at $V_{G} = -60$ V) of photodetector based on 1-P thin film and DPA crystal in dark (blue line) and upon exposure to RCPL (red line) and LCPL (black line) illumination at a wavelength of 556 nm (Supplementary Fig. 16). d Voltage versus current density graph of photodetector in dark, and under 556 nm illumination (Supplementary Fig. 17). e Current-time characteristics (recorded at $V_{G} = -60$ V, with $V_{G}$ switching from 0 V to -60 V) for the photodetector in dark (d) and under 556 nm illumination (e). f Optical switch characteristics of the photodetector under the illumination at a wavelength of 556 nm with the intensity of 84.88 mW cm$^{-2}$.
and CYTOP, which indicates that efficient energy transfer occurs in the donor-acceptor heterojunction (Supplementary Table 8). In addition, SKPM measurements show that the potential of the bilayer heterojunction between the chiral film and the DPA crystal changes under 556 nm irradiation (Fig. 3f, Supplementary Fig. 24). An increase of potential drop at the heterojunction of 1-P film/DPA crystal is detected from dark state to 556 nm illumination, with the potential drop increasing from 54.5 mV (dark state) to 76.1 mV (LCPL irradiation) and then to 89.4 mV (RCPL irradiation). The higher potential drop under RCPL illumination compared with that of LCPL can be attributed to the higher absorbance of 1-P to RCPL, which further confirms the energy transfer between the heterojunction (Fig. 3f). Since no obvious photoresponse signal could be obtained from the OFET based on pure chiral materials under 556 nm illumination, it is speculated that the photocurrent may be caused by the free carriers generated from separated excitons at the interface. Under the dark state, the chiral active layer exists only as ultrathin insulating layer which mainly affects the charge injection of the OFETs. Under the 556 nm laser illumination, similar to the single component OFET, excitons are generated in the chiral active layer upon CP selective absorption. The free holes are injected into the DPA layer which increases the carrier concentration in the channel and enhances the photocurrent of the devices. Meanwhile, the electrons are trapped and accumulate in the chiral active layer, which forms a photoinduction electric field and enhances charge transport property of the holes in the DPA layer. (Supplementary Note 5, Fig. 3g).

Multi-wavelength detection and information transmission. Since the CPL detection wavelength is dependent on the CPL absorption difference of the chiral molecules, one important advantage of our CPL detectors is they can respond to the entire visible light region by selecting proper chiral molecules. For example, we can achieve red (700 nm), green (556 nm) and blue (488 nm) CPL detection based on the donor/acceptor heterojunction strategy. As we mentioned above, chiral molecule NTPH-P exhibits multi CD signals which originate from more than one impressive Cotton effects. Besides 556 nm, 488 nm CPL photodetect can also be realized in NTPH-P/DPA crystal-based detector. The maximum $|g_{ph}|$ factor is relatively low (around 0.15), which may mainly originate from the lower CP selective absorption (Fig. 4a, Supplementary Figs. 25–26). The detection of 700 nm CPL is realized based on another chiral molecule spiro-fused terylene dimer (SDT), which exhibits a sharp and distinct signal in the ellipticity spectra at 700 nm (Supplementary Fig. 27). The corresponding relationship between the
Fig. 3 Response and mechanism of the photodetector. a Change in drain current $I_D$ of the detector in response to CPL illumination. The light responses of LCPL and RCPL are superimposed, and the change of the photocurrent can directly correspond to the photocurrent shown in Fig. 2f. b Photoreponse of the detector to the switch from LCPL to RCPL illumination under different light intensity. c Change of the photocurrent dissymmetry factor exposure to different light intensity illumination. d Change of the circularly dichroism signal and the photocurrent dissymmetry factor of the detector based on different thickness of the 1-P film. e Fluorescence lifetime of DPA on different substrates, silica, CYTOP and 1-P film. f SKPM image of the interface formed by DPA crystal and 1-P film. During the scanning, the bilayer was first placed in the dark condition and then exposed to the laser of 556 nm (from top to the bottom: 556 nm RCPL, 556 nm LCPL, dark). g The mechanism of the CPL photo FETs.

The photocurrent dissymmetry factor and absorption dissymmetry is consistent under the light intensity of 4.58 mW cm$^{-2}$ (Fig. 4f, Supplementary Figs. 30–32). Herein, the time-dependent photoresponse of the crystal and thickness of the crystal are desired for biomedical applications, such as wearable electronics and human skins. For real-time in-situ CPL detection, large-area flexible devices are fabricated by using off state (current in dark) as the data point interval (Fig. 4f). To further confirm that, we decode the light signal based on Morse code encryption. Morse code consists of two basic signals: short dot signals and long dash signals which could be defined by the photocurrent of the device under LCPL and the RCPL. The off state is still an interval of data points, but with a time limit attached. For example, in the signal transmission, the duration of the off states below 10 s represents the interval between dots and dashes, while 10–20 s represents the interval between characters. After simple data processing, we successfully obtain the data of “ICCAS” (Fig. 4g). Through the decryption of data, the content of information transmission can be obtained through electrical signals, which provides the opportunity in optoelectronics for various prospective applications such as quantum information and encryption, biological monitoring, dynamic monitoring and so on.
The NTPH-P/DPA crystal-based photodetector. The blue shading and gray shading are tested with the illumination of LCPL and RCPL, respectively. The red shading and gray shading are tested with the illumination of LCPL and RCPL, respectively. The green shading and gray shading are tested with the illumination of LCPL and RCPL, respectively.

**Methods**

**Materials.** The chiral molecules (NTPH-P, SDT) were prepared by spin-coating from 4 mg mL\(^{-1}\) chloroform-n-hexane solution on the substrate with S/D electrodes. The different thickness of the thin film could be obtained by different spin-coating conditions at 2000 rpm, 3500 rpm, 5000 rpm for 40 s. The fabrication process of the CPL photodetectors is described in the Supplementary.

**Measurements.** UV-Vis spectra were measured with Hitachi (Model U-3010) UV-Vis spectrophotometer on a 1 cm wide quartz plate. Ellipticity spectra were collected on JASCO J-1700 CD spectrometer. The film thickness was determined using Atomic Force Microscope (Cypher ES, Oxford Instruments Asylum Research Inc.). SKPM images were obtained with Bruker Multimode 8. Inverse photoemission spectroscopy measurement was performed using a customized ULVAC-PHI LEIPS instrument with Bremsstrahlung isochromatic mode. Ultraviolet photoelectron spectroscopy was measured with Kratos (AXIS ULTRA DLD). The illumination of linear polarized light was generated through the 556 nm laser (MLG-FN-556), 488 nm laser (MW-BL-488) and 700 nm laser (SC-400, NKT Photonics). The CPL illumination was generated through a quarter-wave plate (Thorlabs, AQWP05M-600). The intensity of LCPL and RCPL light was measured by standard Si detector (Thorlabs, PM100D) to ensure the uniform intensity.

Optoelectronic characteristics were measured by using a semiconductor parameter analyzer Agilent B1500A in the ambient environment at room temperature in dark condition and under illumination. Saturation mobility can be estimated using the equation [Eq. 1]

\[
\mu = \frac{2L}{WC_1} \times \left( \frac{dI_D}{dV_G} \right)^2
\]

where \(I_D\) is the drain–source current, \(W\) is the channel width, \(L\) is the channel length, \(\mu\) is the field-effect mobility, \(C_1\) is the capacitance per unit area of the gate dielectric layer and \(V_G\) and \(V_D\) are the gate voltage and threshold voltage.

As for the optoelectronic characteristics of the CPL detector, the whole test was explored in ambient conditions. The photoresponse were carried out with different laser with linear polarized light of 488 nm (56.07 mW cm\(^{-2}\)), 556 nm (84.88 mW cm\(^{-2}\)) and 700 nm (4.58 mW cm\(^{-2}\)).

**Contact resistance.** The contact resistance of the OFET with the insert chiral layer was calculated by Y-function method.

**Estimation of optoelectronic properties.** In order to investigate properties for photo FETs, responsivity \(R\), external quantum efficiency (EQE) and detectivity \(D^*\) were calculated from transfer characteristics coupled with light irradiation.

**Discussion**

In summary, a novel CPL photodetector based on chiral semiconductor/high mobility semiconductor heterojunction has been designed and demonstrated successfully, which exhibits high sensitivity, long-term stability and multi-wavelength detectability. Importantly, the device structure demonstrated here averts the high mobility requirement of chiral semiconductors. The whole test was explored in ambient conditions. The photoresponse were carried out with different laser with linear polarized light of 488 nm (56.07 mW cm\(^{-2}\)), 556 nm (84.88 mW cm\(^{-2}\)) and 700 nm (4.58 mW cm\(^{-2}\)).

![Image](https://example.com/image.png)

**Fig. 4 Multi-wavelength circularly polarized light detection. a** Real-time \(I_D\) change of the detector in response to 488 nm LCPL and RCPL illumination of the NTPH-P/DPA crystal-based photodetector. The blue shading and gray shading are tested with the illumination of LCPL and RCPL, respectively. **b** Real-time \(I_D\) change in response to the 700 nm LCPL and RCPL illumination of the SDT/DPA crystal-based photodetector. The red shading and gray shading are tested with the illumination of LCPL and RCPL, respectively. **c** Optical microscopy image of the flexible device based on 1-P/DPA crystal. **d** Architecture of the flexible device fabricated on PET substrates. **e** Real-time \(I_D\) change of the detector in response to 556 nm LCPL and RCPL illumination of the flexible photodetector based on NTPH-P/DPA crystal. The green shading and gray shading are tested with the illumination of LCPL and RCPL, respectively. **f, g** Information transmission of flexible photodetector based on 1-P/DPA crystal. The green shading and gray shading are tested with the illumination of LCPL and RCPL, respectively.
The $R$ value is typically defined by the following equations [Eq. 2]:

$$R = \frac{I_{ph}}{P_n} = \frac{I_{light} - I_{dark}}{P_n}$$

(2)

where $I_{ph}$ is the photocurrent, $P_n$ is the incident illumination power on the channel of the device, $I_{light}$ is the drain current under illumination, and $I_{dark}$ is the drain current in the dark.

The EQE value is typically defined by the following equation [Eq. 3]:

$$EQE = \frac{R \cdot h c}{\lambda q I}$$

(3)

where $\lambda$ is the incident-light wavelength, $q$ is the absolute value of electron charge, $h$ is the Planck constant, and $c$ is the speed of light.

The $D^*$ value is typically defined by the following equation [Eq. 4]:

$$D^* = \frac{R}{\sqrt{2qI_{dark}}} = \frac{R\sqrt{A}}{\sqrt{2qI_{dark}}}$$

(4)

where $A$ is the channel area.

Statistics and reproducibility. CPL photodetector can be obtained with similar fabrication for more than 200 independent experiments. More than 100 detectors based on I-P or I-M and more than 20 detectors based on R-SDT or S-SDT were prepared, and similar results were obtained.

Data availability

The data that support the finding of this study are included within the paper and its Supplementary Information files, or available from the corresponding authors upon reasonable request.

Code availability

The code is available at: https://doi.org/10.5281/zenodo.6591397.

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Author contributions

L.J. designed and supervised the project; W.J., Z.M., J.F., J.L., and Z.W. synthesized the compounds; J.L. drawn the device configuration. D.Z. prepared the samples, performed the measurements and carried out the analysis; Y.H. carried out the simulations. C.L. performed measurement and analysis of SKPM with help from D.W., X.Z. constructed the optical path with the help of Y.Z.; J.W. provided insightful advice. D.Z., J.L., and L.J. wrote the paper. All authors contributed to discussions.

Competing interests

The authors declare no competing interests.

Additional information

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