# RESEARCH ARTICLE | FEBRUARY 07 2024

# High-speed and sensitivity near-infrared organic photodetector achieved by halogen substitution strategy for optical wireless communication **FREE**

Special Collection: Organic and Hybrid Photodetectors

Yu Zhu <sup>[</sup>© ; Jing Zhang <sup>[</sup>© ; Hao Qin <sup>[</sup>© ; Guangkun Song; Zhaoyang Yao <sup>[</sup>© ; Zuhao Quan <sup>[</sup>© ; Yanqing Yang <sup>[</sup>© ; Xiangjian Wan <sup>[</sup>© ; Guanghui Li **≅** <sup>[</sup>© ; Yongsheng Chen <sup>[</sup>© ]



Appl. Phys. Lett. 124, 061104 (2024) https://doi.org/10.1063/5.0177229



CrossMark





Export Citatio

# High-speed and sensitivity near-infrared organic photodetector achieved by halogen substitution strategy for optical wireless communication

Cite as: Appl. Phys. Lett. **124**, 061104 (2024); doi: 10.1063/5.0177229 Submitted: 20 September 2023 · Accepted: 19 January 2024 · Published Online: 7 February 2024



### AFFILIATIONS

<sup>1</sup>The Centre of Nanoscale Science and Technology and Key Laboratory of Functional Polymer Materials, Institute of Polymer Chemistry, Renewable Energy Conversion and Storage Center (RECAST), College of Chemistry, Nankai University, Tianjin 300071, China <sup>2</sup>State Key Laboratory of Elemento-Organic Chemistry, Nankai University, Tianjin 300071, China

Note: This paper is part of the APL Special Collection on Organic and Hybrid Photodetectors. <sup>a)</sup>Author to whom correspondence should be addressed: ghli1127@nankai.edu.cn

#### ABSTRACT

High-speed and sensitivity solution-processed organic photodetectors (OPDs) have drawn great attention for their promising applications in next-generation optoelectronics, including optical communication, imaging, autonomous driving, and military security. However, current OPDs commonly suffer from slow response speed due to low charge mobility, significantly hindering their applications in optical wireless communication. Herein, a pair of nonfullerene acceptors (NFAs), featuring a prominent  $\pi$  extension in the central units with respect to Y6, are synthesized with the same backbone but different halogenations in end cap groups, namely, CH-4Cl and CH-4F. The OPD based on CH-4Cl exhibits a remarkably short response time of 270 ns ( $\lambda = 850$  nm) and detectivity of >10<sup>13</sup> Jones in a self-powered mode, improving 34% and 500% compared to the values of OPD with CH-4F NFA, respectively, which ranks the highest speed among self-powered solution-processed binary OPD-based on NFAs. This outstanding performance is attributed to the low trap states and energetic disorders of OPDs with CH-4Cl. Furthermore, the high-speed OPD demonstrates a promising application in high-speed optical wireless communication.

Published under an exclusive license by AIP Publishing. https://doi.org/10.1063/5.0177229

High-speed and sensitivity photodetectors (PDs) are the fundamental pillars in advanced optical systems for various applications, including imaging,<sup>1</sup> autonomous driving,<sup>2</sup> military security,<sup>3</sup> optical etc. Optical communication, in particular, has communication,4-7 emerged as a promising solution to addressing the bandwidth limitation and data traffic in the current communication system, owing to its rich spectrum and high-speed data transmission capabilities.<sup>6,8-10</sup> Currently, inorganic photodetectors, such as Si, Ge, and InGaAs, dominate the mainstream market due to their exceptional performance and mature infrastructure, especially in the fiber-optic communication system.<sup>11</sup> However, these PDs typically suffer from limited detection areas, resulting in low-power reception and necessitating precise beam alignment between transmitters and PDs. Furthermore, the inherent rigid substrate of inorganic PDs makes them unsuitable for emerging wearable electronics that demand large-area and flexible optical signal receivers.

Solution-processed organic photodetectors (OPDs) with bulkheterojunction (BHJ) structures are gaining increasing attention for their tailorable spectra detection, inherent flexibility, lightweight, and ease of large-area processing.<sup>12,13</sup> For optical wireless communication, both response speed and sensitivity of PDs determine the speed, capacity, and accuracy of data transmission.<sup>14</sup> Benefiting from the brilliant advancements in narrow-bandgap nonfullerene acceptors (NFAs), such as YZ1,<sup>15</sup> ITIC,<sup>16</sup> CO1-4Cl,<sup>17</sup> COi8DFIC,<sup>18,19</sup> PDTTIC-4F,<sup>20</sup> OPDs have achieved breakthrough developments in key performance parameters for various applications, even exceeding the performance of inorganic PDs. Nonetheless, the response speed of OPDs still lags behind their inorganic counterparts, hindering their applications in high-speed optical wireless communication. The fundamental reason for this limitation lies in the low charge carrier mobility due to the high energetic disorders and trap states in organic semiconductors.<sup>21</sup> Recently, tremendous efforts, such as central unit,<sup>22</sup> end group,<sup>15</sup> and

side chain tuning strategies,<sup>23–25</sup> have been dedicated to improving charge mobility and reducing charge recombination. Among these strategies, halogenation (F, Cl, Br) of the end group is a relatively simple but significantly effective strategy to tune the chemical and physical properties of NFAs, which can significantly lower both lowest unoccupied molecular orbitals (LUMO) and highest occupied molecular orbitals (HOMO) due to their strong electron-withdrawing ability, thereby markedly broadening the absorption spectra.<sup>26,27</sup> Moreover, the strong non-covalent interactions (e.g., F...H, F...S, and F... $\pi$ ) enhance the intermolecular packing and crystallinity, thereby improving charge mobility.<sup>22,28,29</sup> Despite the extensive studies on the halogenation strategy on organic photovoltaics (OPVs) nearly no research efforts have been devoted to exploring the halogenation strategy for high-speed and sensitivity OPDs.

Recently, we successfully constructed CH series NFAs featuring with a remarkable  $\pi$ -extension in the central unit with respect to Y6.<sup>22,30</sup> This unique structure leads to a more effective and compact 3D molecular packing network, which contributes to high charge mobility and low energetic disorder.<sup>22,30</sup> In this study, by facilely substituting the F atom with the Cl atom on the end group of CH-NFAs, namely, CH-4F and CH-4Cl, we simultaneously improved the response speed and sensitivity of visible-near-infrared (Vis-NIR) OPDs. The resulting device based on CH-4Cl exhibits a significantly short response time of 270 ns, ranking the highest response speed among solution-processed binary OPDs based on NFAs. Moreover, the device with CH-4Cl shows a high detectivity of over 10<sup>13</sup> Jones, a large linear dynamic range of over 154 dB, and a peak responsivity of 0.51 A W<sup>-1</sup> at 800 nm, exceeding all the corresponding values of OPDs with CH-4F. This promising result originates from the reduced trap states and energetic disorders in the photoactive film with CH-4Cl NFAs, leading to improved charge mobility and reduced charge recombination in OPDs. Furthermore, the OPD based on PM6:

CH-4Cl demonstrates promising potential applications in high-speed optical wireless communication.

As depicted in Fig. 1(a), CH-4F and CH-4Cl have the same backbone, featuring with  $\pi$ -extension in the central unit with respect to Y6, but different end groups modified with Cl and F atoms. Here, we selected polymer PM6 as a donor due to its suitable energetic level and complementary absorption spectra with CH-4Cl and CH-4F [Figs. 1(a) and S1(a)]. These acceptors have exhibited excellent photovoltaic performance in OPVs, ensuring the high external quantum efficiency (EQE) (Fig. S2).<sup>22</sup> To efficiently suppress the hole/electron injection from electrodes under bias, we selected ZnO and MoOx as the hole and electron blocking layers, respectively [Fig. 1(b)]. Therefore, devices with an inverted architecture of indium tin oxide (ITO)/ZnO:PFN-Br/ active layer/MoOx/Ag were prepared [Fig. 1(b)]. The detailed synthetic routes and characterizations of CH-4Cl and CH-4F NFAs and device fabrication process are described in the supplementary material. In the solution state, both CH-4Cl and CH-4F NFAs demonstrate strong absorption in the NIR region of 700-800 nm, where the maximum absorption peaks ( $\lambda_{max}$ ) of CH-4Cl and CH-4F are located around 756 and 742 nm, respectively. From the solution to a film state, the absorption spectra of CH-4Cl and CH-4F NFAs both exhibit redshift by 60 and 66 nm [Fig. 1(c)], respectively. Despite the Cl atom has a larger atomic radius and weaker electron-withdrawing ability compared to the F atom, the CH-4Cl NFA exhibits a broader spectra absorption, which is owing to the stronger intermolecular  $\pi$ - $\pi$  packing caused by the larger atomic size of chlorine and larger length of the chlorine-carbon bond (Fig. S3).<sup>31</sup> Moreover, the CH-4Cl film shows a sharper absorption edge than the CH-4F, implying that there are less energetic disorders in the CH-4Cl film due to the strong  $\pi$ - $\pi$  interaction. The HOMO of donors and acceptors were measured via the electrochemical cyclic voltammetry (CV) technique [Fig. S1(b)].



FIG. 1. (a) Chemical structures of donors and acceptors; (b) schematic structure of OPDs with inverted structure; (c) absorption profiles of acceptors; and (d) energy diagrams of materials used in OPDs.

19 February 2024 05:53:07

The LUMO were further determined through the combination of absorption spectra and HOMO values of NFAs. It should be noted that from the fluorinated CH-4F to chlorinated CH-4Cl, the HOMO (-5.68 to -5.73 eV) and LUMO (-3.84 to -3.92 eV) exhibit a downshift, which could be attributed to the empty orbitals of chlorine atoms [Fig. 1(d)].<sup>25</sup>

In order to achieve ultraweak optical signal detection, it is crucial to suppress noise current, especially the shot noise caused by dark current, for improving the sensitivity of OPDs. Therefore, a small reverse bias or a photovoltaic mode is commonly employed in NIR OPDs to minimize dark current. As shown in Fig. 2(a), whichever type of operation mode is utilized, the OPD based on CH-4Cl exhibits a relatively low dark current in comparison to the OPD based on CH-4F. In the photovoltaic mode, the noise current of OPD achieved as low as 1.5 pA, which is five times lower than CH-4F-based OPD (7.4 pA) (Fig. S4). To further evaluate their spectra response, the responsivity (R), a critical figure-of-merit to quantify the sensitivity of OPD, is calculated using EQE as follows:<sup>32</sup>

$$R\left(\frac{A}{W}\right) = \frac{EQE}{100\%} \times \frac{\lambda}{1240\,(\mathrm{nm}\,\mathrm{W}\,\mathrm{A}^{-1})},\tag{1}$$

where  $\lambda$  is the wavelength of the incident light. As depicted in Fig. 2(b), both OPDs with CH-4Cl and CH-4F demonstrate broad and substantial responsivities across the visible and NIR regions, which well aligns with their absorption profiles. Moreover, the OPD with CH-4Cl exhibits a slightly higher responsivity the device with CH-4F in the NIR region, reaching over 0.5 A W<sup>-1</sup> at 800 nm under zero bias.

In addition to responsivity, the specific detectivity ( $D^*$ ), another important figure of merit for photodetectors, is frequently employed to evaluate the sensitivity of OPDs with different device areas, which can be derived as follows:<sup>32</sup>

$$D^* = \frac{\sqrt{A}}{NEP} = \frac{R\sqrt{A}}{S_n},\tag{2}$$

where A is the active device area and  $S_n$  is the noise spectral density. When operated at high reverse bias, the noise current in OPD is dominated by the shot noise expressed as  $(2qJ_d)^{1/2}$ , where q is the elementary charge. The resulting OPD with CH-4Cl exhibits a specific detectivity of over  $10^{13}$  Jones (Jones = cm Hz<sup>1/2</sup>/W) within the 350–900 nm range in the self-powered mode, which is five times higher than that of OPD with CH-4F. The maximum  $D^*$  of the tested OPD with CH-4Cl is  $8 \times 10^{13}$  Jones at 800 nm. To avoid the overestimation of the  $D^*$  of OPD, we initially conducted a current–time (*I–T*) measurement at zero bias and obtained the noise spectral via the fast Fourier transform shown in Fig. S5.

As discussed above, response time is a crucial parameter for OPDs applied in optical wireless communication. To mitigate the overestimation of response speed, herein, we introduced steady-state electric current measurement in both dark and light-irradiation conditions ( $\lambda = 850$  nm), instead of commonly reported transient photocurrent (TPC) measurement. As shown in Fig. 2(d), the OPD with CH-4Cl exhibits a rise time of 270 ns and a fall time of 289 ns at zero bias (time to go from 10% to 90% of the steady-state response), which significantly decrease around 34% and 18% compared to the OPD



FIG. 2. (a) Current density–voltage (J–V) curves of OPDs based on CH-4CI and CH-4F NFAs in the dark; (b) spectral responsivity profiles of CH-4CI and CH-4F NFAs-based OPDs; (c) specific detectivities of CH-4CI and CH-4F-based OPDs at wavelengths ranging from 300 to 1000 nm; (d) time domain responses of CH-4CI and CH-4F-based OPDs; (e) -3 dB cutoff frequency of CH-4CI and CH-4F-based OPDs; and (f) LDRs of CH-4CI and CH-4F-based OPDs under the irradiation of NIR light ( $\lambda = 850 \text{ nm}$ ) at zero bias.

with CH-4F ( $\tau_{rise}$  = 409 and  $\tau_{fall}$  = 354 ns). The corresponding  $f_{-3dB}$  bandwidth of the optimal OPD based on CH-4Cl achieves 1.01 MHz in the self-powered mode under NIR light irradiation generated by an 850 nm LED, which is 21.4% higher than the OPD with CH-4F [Fig. 2(e)], ensuring the high-speed data transmission capability in optical wireless communication systems.

The linear dynamic range (LDR) signifies the capability of OPDs to maintain a consistent responsivity over a broad range of incident light intensities. It is theoretically described as follows:<sup>32</sup>

$$LDR = 20 \times \log \left[ \frac{J_{\text{max}}}{J_{\text{min}}} \right],$$
 (3)

where  $J_{\text{max}}$  and  $J_{\text{min}}$  are the photocurrent densities measured at the maximum and minimum light intensity, respectively. Under highintensity incident light irradiation, the bimolecular recombination caused by a high carrier concentration and the serial resistance of the OPD are dominant factors for the upper limit of the LDR, which has been fully investigated in organic solar cells. In contrast, the lower limit of the LDR is generally dependent on the NEP of OPD. The estimated LDR values for devices with CH-4Cl and CH-4F exceed 154 and 143 dB, respectively [Fig. 2(f)]. Despite a similar photocurrent density gradient over the light intensity, the LDR of the device with CH-4Cl is higher than that for the device with CH-4F owing to a lower dark current at 0 V bias.

According to the following formula:  $f_{-3dB}^{-2} = (\frac{3.5}{2\pi t})^{-2} + (\frac{1}{2\pi RC})^{-2}$ , the response speed of OPD is simultaneously determined by both carrier transit time and resistance–capacitance (*RC*) time constant, which is directly associated with trap states and energetic disorders in the photoactive film.<sup>30</sup> In the Vis–NIR OPD, the primary source of the noise current is the excitation of free charges from the HOMO edge of the donor to the LUMO edge of the acceptor under the assistance of trap states. Therefore, the energetic disorder and trap states are closely related to the noise current.<sup>5,33</sup> To enlighten the origin of the fast response speed and high detectivity of OPDs, here, we systematically investigate the charge trap states and energetic disorder in the photoactive films. As it is rather challenging to directly measure traps in organic solids due to the lack of a simple technique to access their concentrations, we probe these traps by conducting the capacitance–voltage (C–V) measurement of OPDs.

As shown in Fig. 3(a), the OPD with CH-4Cl exhibits a lower capacitance (0.6 nF) than the device prepared with CH-4F (1.3 nF) when operating in the photovoltaic mode, leading to a lower RC time



FIG. 3. (a) Mott–Shockley plots of OPDs based on CH-4CI and CH-4F NFAs; (b) Urbach energy of OPDs based on CH-4CI and CH-4F NFAs; and (c) the dependence of capacitance on frequency of OPD with CH-4CI with different device areas. (d) The dependence of response time on size of OPD based on CH-4CI.

19 February 2024 05:53:07

constant. According to the Mott-Shockley analysis at various bias voltages, the trap density of the CH-4Cl-based OPD is as low as  $1.3 \times 10^{16}$  cm<sup>-3</sup>, which is significantly lower than the device of CH-4F NFA with the concentration of  $2.11 \times 10^{16}$  cm<sup>-3</sup>. Energetic disorder is another key factor that dominates the charge mobility and dark current of OPDs with BHJ structures.<sup>5</sup> Here, we introduced the Urbach energy  $(E_U)$  to describe the width of the tails of the electronic density of states (DOS).<sup>30</sup> Remarkably, the CH-4Cl-based OPD exhibits a considerably lower E<sub>U</sub> value of 21.86 meV compared to the CH-4F-based device of 23.15 meV [Fig. 3(b)]. The decreased Urbach energy benefits the reduction in the energetic disorder, thus effectively minimizing charge recombination and improving charge transport.<sup>21</sup> This promising result suggests that the introduction of the Cl atom in the end group of NFAs could effectively reduce trap states and energetic disorders in the photoactive films. As depicted in Fig. 3(c), the geometrical capacitance of OPD is directly proportional to the effective area size of the device, which decreases with the reducing area of devices. Consequently, the response time of OPD decreases with the reduced area sizes of OPDs [Fig. 3(d)].

To investigate the charge recombination process in CH-4Cl and CH-4F-based OPDs, we examined the relationship between  $J_{SC}$  and  $P_{Light}$  at various light intensities. As shown in Fig. 4(a), the relationship

between  $J_{SC}$  and  $P_{Light}$  is defined as  $J_{SC} \propto P^{\alpha}$ , with *a* indicating a recombination parameter. When *a* is close to 1, the bimolecular recombination in BHJ is negligible. The resulting values of *a* for OPDs with CH-4Cl and CH-6F are 0.988 and 0.984, respectively, revealing that the charge recombination in the CH-4Cl-based device is more efficiently suppressed.<sup>22</sup> Furthermore, the trap-assisted recombination behavior was studied by exploring the relationship between  $V_{OC}$  and  $\ln(P_{Light})$  displayed in Fig. S7. The slope of the curve for CH-4Cl-based device is 1.15, slightly lower than that of the CH-4F-based device. The smaller slope observed in the CH-4Cl-based device indicates that the trap-assisted recombination has been suppressed, leading to an improved responsivity, charge mobility, and LDR of OPD. To understand the charge generation and extraction properties of OPDs, we conducted the photocurrent density  $(J_{ph})$  vs the effective voltage  $(V_{eff})$  measurement, which are calculated as follows:<sup>30</sup>

$$J_{ph} = J_L - J_D, \tag{4}$$

$$V_{eff} = V_0 - V_a, \tag{5}$$

where  $J_L$  is the photocurrent density under illumination,  $J_D$  is the dark current density,  $V_0$  is the voltage at which  $J_{ph} = 0$ , and  $V_a$  is the applied voltage. With the increase in  $V_{eff}$   $J_{ph}$  reaches a saturation ( $J_{sat}$ ),



FIG. 4. (a) J<sub>ph</sub>-V<sub>eff</sub> plots of the devices based on optimized PM6:CH-4F and PM6:CH-4Cl. (b) Dependences of current density (J<sub>sc</sub>) on P<sub>in</sub> light of optimized OPD. (c) Histograms of the electron mobility and hole mobilities of OPDs based on CH-4Cl and CH-4F. (d) Summary of response time and responsivity of high-speed OPDs with different NFAs (details in Fig S6).

indicating an efficient exciton dissociation and nearly complete charge collection by electrodes. The exciton collection ability of OPD can be evaluated by the  $J_{SC}/J_{sat}$  ratio, where  $J_{SC}$  is the short-circuit current density. Figure 4(b) shows  $J_{SC}/J_{sat}$  ratios of OPDs with CH-4Cl and CH-4F are 98.1% and 97.3%, respectively. This indicates that the CH-4Cl-based OPD demonstrates superior exciton collection efficiency, thereby improving photocurrent and responsivity. All these factors contribute to an improved charge mobility in the OPD with CH-4Cl. Consequently, the CH-4Cl-based OPD demonstrates higher hole and electron mobilities  $(8.27 \times 10^{-4} \text{ and } 6.06 \times 10^{-4} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1})$  than the device with CH-4F (7.89 and  $5.35 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ ) acquired by space charge limited current (SCLC) (Fig. S8), with a more balanced mobility ratio of 1.36, close to the ideal values shown Fig. 4(c). As summarized in Fig. 4(d), the OPD with CH-4Cl demonstrated the highest response speed in the NIR region compared to other OPDs with NFAs prepared via the solution process.

Taking advantage of the CH-4Cl-based OPDs that exhibit high-speed and sensitivity characteristics, we seamlessly integrated them into an optical wireless communication system as a signal receiver to capture information conveyed through NIR light. As shown in Fig. 5(a), the information generated by a signal generator is initially encoded using the American Standard Code for Information Interchange (ASCII), employing a binary format of "0" and "1." Through modulation, the signal generator amplifies the high and low voltage levels to drive the LED ( $\lambda = 850 \text{ nm}$ ), which emits NIR light and converts the information into optical signals. Subsequently, the OPD receives the optical signal and efficiently converts it into electric signals displayed on the oscilloscope. The resulting response waveforms observed on the oscilloscope represent a binary code of "0" and "1," with high and low photovoltages corresponding to each, respectively. As depicted in Fig. 5(b), a specific word, such as "N, K, U," is generated and transmitted to NIR OPD for demonstration purposes.

In summary, high-speed and high-sensitivity visible-to-NIR broadband OPDs have been realized through the strategy of halogen



FIG. 5. Optical communication application. (a) Schematic of optical communication setup. (b) The signal composed of an ACSII binary code for NKU and received by OPD.

substitution on end groups of NFAs. Compared to OPDs with CH-4F NFA, the device prepared with CH-4Cl NFA exhibits a short response time of 270 ns in the self-powered mode, ranking the highest response speed among solution-processed binary OPDs. Moreover, the CH-4Cl-based OPD demonstrates a specific detectivity of  $8 \times 10^{13}$  Jones, peak responsivity of 0.51 A W<sup>-1</sup> at 800 nm, LDR of 154 dB, and a -3 dB cutoff frequency of 1.01 MHz. This outstanding performance originates from the low charge trap states and energetic disorders in the photoactive films with CH-4Cl NFA. Furthermore, the high-speed and sensitivity OPD can work as the light signal receiver, which shows promising application potential in optical wireless communication for AI, Internet of Things, and automation. The result of this work is not only of great academic interest but also of widespread application interest for next-generation optoelectronics.

See the supplementary material for more details on the fabrication of OPD, measurement, absorption spectra, cyclic voltammograms, noise spectral density, current transients, and measurements of hole and electron mobility.

We gratefully acknowledge the financial support from NSFC (Nos. 21935007 and 52025033), MoST (Nos. 2022YFB4200400 and 2019YFA0705900), and the National Basic Research Program (No. 2022YFA1203304) of China.

# AUTHOR DECLARATIONS Conflict of Interest

The authors have no conflicts to disclose.

#### **Author Contributions**

Yu Zhu and Jing Zhang contributed equally to this work.

Yu Zhu: Data curation (equal). Jing Zhang: Data curation (equal). Hao Qin: Data curation (supporting). Guangkun Song: Data curation (supporting). Zhaoyang Yao: Supervision (supporting). Zuhao Quan: Data curation (supporting). Yanqing Yang: Data curation (supporting). Xiangjian Wan: Supervision (supporting). Guanghui Li: Conceptualization (lead); Data curation (equal); Funding acquisition (equal); Investigation (equal); Supervision (lead); Writing – original draft (lead); Writing – review & editing (lead). Yongsheng Chen: Conceptualization (lead); Data curation (lead); Funding acquisition (lead); Investigation (lead); Supervision (lead); Writing – original draft (equal); Writing – review & editing (equal); Writing – original draft (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.

# REFERENCES

<sup>1</sup>J. J. Kim, Y. Wang, H. Y. Wang, S. Lee, T. Yokota, and T. Someya, Adv. Funct. Mater. **31**, 2009602 (2021).

- <sup>2</sup>A. Morteza Najarian, M. Vafaie, A. Johnston, T. Zhu, M. Wei, M. Saidaminov, Y. Hou, S. Hoogland, F. P. Garcia de Arquer, and E. H. Sargent, Nat. Electron. 5, 511 (2022).
- <sup>3</sup>G. H. Li, M. Suja, M. G. Chen, E. Bekyarova, R. C. Haddon, J. L. Liu, and M. E. Itkis, ACS Appl. Mater. Interfaces 9, 37094 (2017).
- <sup>4</sup>Y. Zhu, C. Geng, L. Hu, L. Liu, Y. Zhu, Y. Yao, C. Li, Y. Ma, G. Li, and Y. Chen, Chem. Mater. 35, 2114 (2023).

- <sup>5</sup>Y. Zhu, H. Chen, R. Han, H. Qin, Z. Yao, H. Liu, Y. Ma, X. Wan, G. Li, and Y. Chen, "High-speed flexible near-infrared organic photodiode for optical communication" Natl. Sci. Rev. 11, nwad311 (2024).
- <sup>6</sup>T. Mueller, F. Xia, and P. Avouris, Nat. Photonics 4, 297 (2010).
- <sup>7</sup>H. Wang, C. Zhang, W. Chan, S. Tiwari, and F. Rana, Nat. Commun. 6, 8831 (2015).
- <sup>8</sup>J. F. Tasker, J. Frazer, G. Ferranti, E. J. Allen, L. F. Brunel, S. Tanzilli, V. D'Auria, and J. C. F. Matthews, Nat. Photonics **15**, 11 (2021).
- <sup>9</sup>S. N. Ismail and M. H. Salih, AIP Conf. Proc. 2213, 020289 (2020).
- <sup>10</sup>H. Haas, L. Yin, Y. Wang, and C. Chen, J. Lightwave Technol. 34, 1533 (2016).
- <sup>11</sup>L. Grobe, A. Paraskevopoulos, J. Hilt, D. Schulz, F. Lassak, F. Hartlieb, C. Kottke, V. Jungnickel, and K. D. Langer, IEEE Commun. Mag. **51**, 60 (2013).
- <sup>12</sup>D. Z. Yang and D. G. Ma, Adv. Opt. Mater. 7, 1800522 (2019).
- <sup>13</sup>P. C. Y. Chow and T. Someya, Adv. Mater. **32**, 1902045 (2020).
- <sup>14</sup>M. Romagnoli, V. Sorianello, M. Midrio, F. H. L. Koppens, C. Huyghebaert, D. Neumaier, P. Galli, W. Templ, A. D'Errico, and A. C. Ferrari, Nat. Rev. Mater. 3, 392 (2018).
- <sup>15</sup>Y. J. Xia, C. Geng, X. Q. Bi, M. P. Li, Y. Zhu, Z. Y. Yao, X. J. Wan, G. H. Li, and Y. S. Chen, Adv. Opt. Mater. 11, 2301518 (2023).
- <sup>16</sup>J. S. Liu, J. Z. Jiang, S. P. Wang, T. F. Li, X. Jing, Y. L. Liu, Y. X. Wang, H. Wen, M. N. Yao, X. W. Zhan, and L. Shen, Small **17**, 2101316 (2021).
- <sup>17</sup>J. Huang, J. Lee, J. Vollbrecht, V. V. Brus, A. L. Dixon, D. X. Cao, Z. Zhu, Z. Du, H. Wang, K. Cho, G. C. Bazan, and T.-Q. Nguyen, Adv. Mater. **32**, e1906027 (2020).
- <sup>18</sup> W. Li, Y. L. Xu, X. Y. Meng, Z. Xiao, R. M. Li, L. Jiang, L. H. Cui, M. J. Zheng, C. Liu, L. M. Ding, and Q. Q. Lin, Adv. Funct. Mater. **29**, 1808948 (2019).
- <sup>19</sup>Y. Song, G. Yu, B. M. Xie, K. Zhang, and F. Huang, Appl. Phys. Lett. **117**, 093302 (2020).
- <sup>20</sup>Y. J. Chen, Y. Q. Zheng, Y. Y. Jiang, H. J. Fan, and X. Z. Zhu, J. Am. Chem. Soc. **143**, 4281 (2021).

- <sup>21</sup>V. Coropceanu, J. Cornil, D. A. da Silva, Y. Olivier, R. Silbey, and J. L. Bredas, Chem. Rev. **107**, 926 (2007).
- <sup>22</sup>Y. L. Zou, H. B. Chen, X. Q. Bi, X. Y. Xu, H. B. Wang, M. L. Lin, Z. F. Ma, M. T. Zhang, C. X. Li, X. J. Wan, G. K. Long, Y. Zhaoyang, and Y. S. Chen, Energy Environ. Sci. **15**, 3519 (2022).
- <sup>23</sup>J. Y. Wu, J. Luke, H. K. H. Lee, P. S. Tuladhar, H. Cha, S. Y. Jang, W. C. Tsoi, M. Heeney, H. Kang, K. Lee, T. Kirchartz, J. S. Kim, and J. R. Durrant, Nat. Commun. 10, 5159 (2019).
- <sup>24</sup>C. Li, J. D. Zhou, J. L. Song, J. Q. Xu, H. T. Zhang, X. N. Zhang, J. Guo, L. Zhu, D. H. Wei, G. C. Han, J. Min, Y. Zhang, Z. Q. Xie, Y. P. Yi, H. Yan, F. Gao, F. Liu, and Y. M. Sun, Nat. Energy 6, 605 (2021).
- <sup>25</sup>M. Deng, X. P. Xu, Y. W. Duan, L. Y. Yu, R. P. Li, and Q. Peng, Adv. Mater. 35, 2210760 (2023).
- <sup>26</sup>D. Q. Hu, Q. G. Yang, Y. J. Zheng, H. Tang, S. Chung, R. Singh, J. Lv, J. H. Fu, Z. P. Kan, B. Qin, Q. Q. Chen, Z. H. Liao, H. Y. Chen, Z. Y. Xiao, K. Sun, and S. R. Lu, Adv. Sci. 8, 2004262 (2021).
- <sup>27</sup>W. C. Zhao, S. S. Li, H. F. Yao, S. Q. Zhang, Y. Zhang, B. Yang, and J. H. Hou, J. Am. Chem. Soc. **139**, 7148 (2017).
- <sup>28</sup>H. Yang, C. Cui, and Y. Li, Acc. Mater. Res. 2, 986 (2021).
- <sup>29</sup>K. Reichenbacher, H. I. Suss, and J. Hulliger, Chem. Soc. Rev. 34, 22 (2005).
- <sup>30</sup>H. B. Chen, Y. L. Zou, H. Z. Liang, T. F. He, X. Y. Xu, Y. X. Zhang, Z. F. Ma, J. Wang, M. T. Zhang, Q. W. Li, C. X. Li, G. K. Long, X. J. Wan, Z. Y. Yao, and Y. S. Chen, Sci. China Chem. **65**, 1362 (2022).
- <sup>31</sup>Y. Cui, H. Yao, J. Zhang, T. Zhang, Y. Wang, L. Hong, K. Xian, B. Xu, S. Zhang, J. Peng, Z. Wei, F. Gao, and J. Hou, Nat. Commun. **10**, 2515 (2019).
- <sup>32</sup>F. P. G. de Arquer, A. Armin, P. Meredith, and E. H. Sargent, Nat. Rev. Mater. 2, 16100 (2017).
- <sup>33</sup>Z. Lu, Y. Xu, Y. Yu, K. Xu, J. Mao, G. Xu, Y. Ma, D. Wu, and J. Jie, Adv. Funct. Mater. **30**, 1907951 (2020).