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Deriving the linear dynamic range of next-generation thin-film photodiodes: Pitfalls and guidelines

Special Collection: Organic and Hybrid Photodetectors

Hrisheekesh Thachoth Chandran ; Sudhi Mahadevan ; Ruijie Ma ; Yu Tang ; Tao Zhu ; Furong Zhu ; Sai-Wing Tsang ; Gang Li

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Hrisheekesh Thachoth Chandran,[1] Sudhi Mahadevan,[2] Ruijie Ma,[1] Yu Tang,[3] Tao Zhu,[1] Furong Zhu,[3] Sai-Wing Tsang,[2] and Gang Li[1,a)]

AFFILIATIONS

[1]Department of Electrical and Electronic Engineering, Research Institute for Smart Energy (RISE), Photonics Research Institute (PRI), The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, People's Republic of China
[2]Department of Materials Science and Engineering, Center of Super-Diamond and Advanced Films (COSDAF), Hong Kong Institute of Clean Energy (HKICE), City University of Hong Kong, Hong Kong, People's Republic of China
[3]Department of Physics, Research Centre of Excellence for Organic Electronics, Institute of Advanced Materials, Hong Kong Baptist University, Kowloon Tong, Hong Kong, China

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[a)]**Author to whom correspondence should be addressed:** gang.w.li@polyu.edu.hk

ABSTRACT

With the use of next-generation semiconductors, notably organic and perovskite materials with remarkable optoelectronic and mechanical properties, thin-film photodiodes are progressing rapidly to rival their inorganic counterparts. However, to ensure a trustworthy comparison among the reported works, it is imperative that the measurement techniques for the figure of merits be unified and standardized. In this Letter, the possible causes of misrepresentation in the linear dynamic range (LDR) values are thoroughly discussed. The role of unity slope in defining the deviation point is examined, and the chances of misinterpretation when adopting different definitions are explained using a representative organic photodiode system. Furthermore, certain criteria are put out to standardize the LDR representation, which could be a crucial step toward facilitating the progress in this promising field via a more rational comparison of literature reports.

Photodiodes (PDs) are a crucial component in electronic systems that are used for a wide variety of purposes, such as imaging, health monitoring, optical communication, quality inspection, surveillance, and so on.[1,2] The current PD market is mainly led by inorganic materials such as silicon and other compound semiconductors because of their excellent performance metrics, operational stability, and mature fabrication process.[3] However, next-generation applications, which demand mechanically flexible and stretchable PDs that can be conformally attached to the human skin, may not always be satisfied with these PDs formed on rigid substrates.[4,5] The next-generation materials, such as organic semiconductors and organic–inorganic perovskite semiconductors, are perfect fit for this scenario due to their excellent mechanical properties, tunable optoelectronic characteristics, ease of processing, potentially lower cost, monolithic integrability with silicon readout circuitry, and so on.[6–8] Considerable attention has been devoted to the development of PDs based on these materials, and the development has reached a point wherein the performance metrics are beginning to compete with inorganic counterparts.[9,10] However, the fundamental physical processes and the electro-optical characteristics of these PDs vary significantly from the inorganic PDs.[11–13]

The major concern about this evolving and rapidly progressing field is to validate and compare the performance metrics of reported works. It has been noted and reported that many of the performance metrics are prone to misinterpretation or complete failure at worst, due to the non-standardized and ill-defined methods of performance characterization.[14] In order to address this crucial issue, few significant works have reported guidelines for accurate characterization, particularly with regard to noise equivalent power (NEP) and specific detectivity (D^*).[9,14] These works exposed that the orders of magnitude difference in the values are largely due to the variety of estimation methods adopted for deriving the specific performance metrics. Linear dynamic range (LDR), another key performance metric, also needs to be considered immediately because reported values in the literature vary by orders of magnitude, and it appears that more and more remarkable values are being reported recently.[15] In this Letter, we expose some of the critical factors that if not properly addressed, may lead to the misinterpretation/overestimation of the LDR values in thin-film organic photodiode and propose a standardized method to accurately derive the corresponding values.

LDR in simple terms quantifies the light sensors' capacity to capture variations in light intensity throughout and within the scene to be captured. It is defined by

$$LDR = 20\log\frac{J_{upper}}{J_{lower}} = 20\log\frac{L_{upper}}{L_{lower}}, \quad (1)$$

where L stands for input irradiance in W cm^{-2}, and J stands for photocurrent density in A cm^{-2}. The upper and lower terms correspond to the maximum and minimum input irradiance of the light source and the associated photocurrent produced in the photodiodes.[16,17] Even though the equation looks fairly simple and straightforward, the method of accurate estimation of maximum and minimum values for input irradiance and photocurrent is challenging and is prone to misinterpretation. To determine the LDR, two definitions are generally adopted and are given as follows: Definition-1: the range within which the photodetector output scales linearly with the input light intensity. Definition-2: the light intensity range within which the responsivity (electrical output per optical input, unit of A W^{-1}) of the photodetector remains constant. The two definitions can be related as follows: Within the linear range, the processes of charge carrier generation and recombination are independent of the light intensity, resulting in a constant responsivity. Both definitions are interchangeably used in the literature, wherein the definition-1 is more frequently adopted. This Letter has been structured to highlight several presumptions that could cause the calculated LDR value in both definitions to be interpreted incorrectly, and we have contrasted the values in each scenario.

Figure 1 represents the home-built measurement setup for the LDR measurement. The system is modified from its default setting for sensitive photovoltaic external quantum efficiency (EQE) measurement/electro-absorption (EA) measurement.[18,19] This AC detection technique is capable of detecting low-level optical signals with a better signal to noise ratio (S/N). A detailed description and the advantages of this measurement approach are discussed later. The light intensity variation is accurately controlled by a combination of a dual neutral density (ND) filter wheel and a single ND filter wheel placed in the optical path. The sensitive measurement system can accurately measure input light intensity (at 830 nm monochromatic light corresponding to the above-bandgap photoexcitation of the active material system) up to 10^{-10} W cm^{-2}, and the measurable maximum light intensity is around 10^{-2} W cm^{-2} using a calibrated silicon detector (Thorlabs DET100A). Around 23 data points are measured throughout these 8 orders of magnitude input irradiation, and at each intensity, at least two measurements are carried out to ensure repeatability. A custom-written Lab-VIEW program is used for data acquisition. The responsivity (R) and the corresponding J are collected at each intensity and the respective data points are plotted based on definition-1 or definition-2 to get the corresponding LDR values. Moreover, the measurements are done at three different operational applied biases, such as 0 V (self-powered mode), −0.1, and −1 V to understand the influence of applied bias on the LDR value. The device structure of the representative organic photodiode is given in the inset of Fig. 1(b). ITO is used as the bottom electrode, PEDOT: PSS as the hole transport layer/electron-blocking layer (EBL), PBDB-T as the

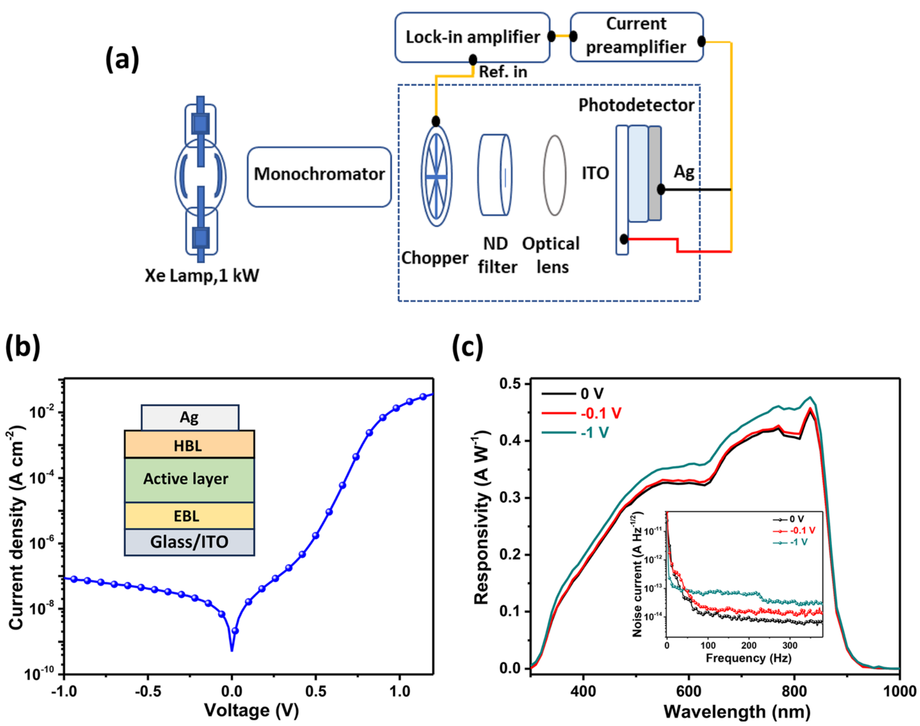

FIG. 1. (a) Schematic representation of the home-built setup for the measurement of LDR. (b) Dark J–V characteristics of the PBDB-T:PY-IT organic photodiode and the device architecture of the corresponding device is given in the inset. (c) The responsivity spectra of PBDB-T:PY-IT device at different applied biases. Inset is the experimentally measured noise current at different applied biases.

donor and PY-IT as the acceptor to form the active layer, PFN-Br as the electron transport layer/hole-blocking layer (HBL), and silver as the top electrode/cathode. The active layer thickness is measured to be around 300 nm. The typical current density–voltage (J-V) characteristics at dark is given in Fig. 1(b), and the responsivity spectra at different applied biases are given in Fig. 1(c). The R is peaked at 830 nm and maintains >0.2 A W^{-1} over a broad wavelength range (350–870 nm). Considering the experimentally measured noise current, the values are, respectively, 8 fA $Hz^{-1/2}$ ($\sim$0 V), 16 fA $Hz^{-1/2}$ (-0.1 V), and 60 fA $Hz^{-1/2}$ (-1 V), denoting the characteristics of an ultra-low noise photodiode.

First, let us take definition-1 into consideration. The LDR is derived from the double logarithmic plot in which the linear fit should have a unity slope. It is to be noted that the unity slope has a very important role in determining the deviation point from the linearity. The deviation point in this work is defined as the final point in the linearity and beyond or below which the detector output deviates from the linearity. From the reported works, only a few of the groups strictly adhere to the unity slope, and in many cases, it is either higher or lower than unity.[20] We have derived the LDR value (at -0.1 V) for the system studied in this work with different slopes (Fig. 2). The LDR value determined from the unity slope is 125 dB, and the deviation point is denoted as "A." When it comes to slope 1.01, the LDR has increased to 130 dB, and the deviation point is further extended to point "B." Similarly, the LDR value has increased, respectively, to 137 and 145 dB when the slope is 1.02 and 1.04 with deviation point "C" and "D." These differences in LDR values highlight how crucial it is to derive the LDR value at unity slope; otherwise, the value could be overestimated.[15]

The significance of unity slope in definition-1 has been established; now, the LDR values obtained from definition-2 are assessed and contrasted with those obtained from definition-1. It is noted that the subtle nonlinearities in the light-dependent behavior of J_{ph} become more apparent when representing the responsivity (or EQE) as a function of light intensity, as opposed to the commonly adopted double log plot depicting J_{ph} against light intensity (definition-1). Figure 3 represents the LDR values determined from definition-1 and definition-2 at different applied biases. It is worth noting that there is a widespread practice in assuming constant R throughout the illumination range all the way up to NEP, which denotes the smallest optical power that can be resolved from the photodetector noise.[21] However, there are a number of examples in thin-film detectors wherein the responsivity gradually gets reduced when the light intensity reduces and is mainly attributed to the presence of deep traps related recombination.[22] Having noted that, by measuring the responsivity in the experimentally convenient range and assuming that the responsivity stays constant until the NEP range has resulted in orders of magnitude higher LDR value in the literature. If the noise level [inset of Fig. 1(c)] is considered as the lowest limit of linearity in the case of the representative system, the LDR value can be at least 5 orders of magnitude greater than the value that has already been experimentally determined, and the associated range can easily surpass 200 dB. Hence, assuming noise level or NEP as the lower limit without sufficient experimental measurement support is seen as a significant inaccuracy in the LDR calculation. A further concern is that the so-called "constant value" of responsivity is inadequately defined, and there is no absolute threshold for the permissible deviation from the constant regime. According to

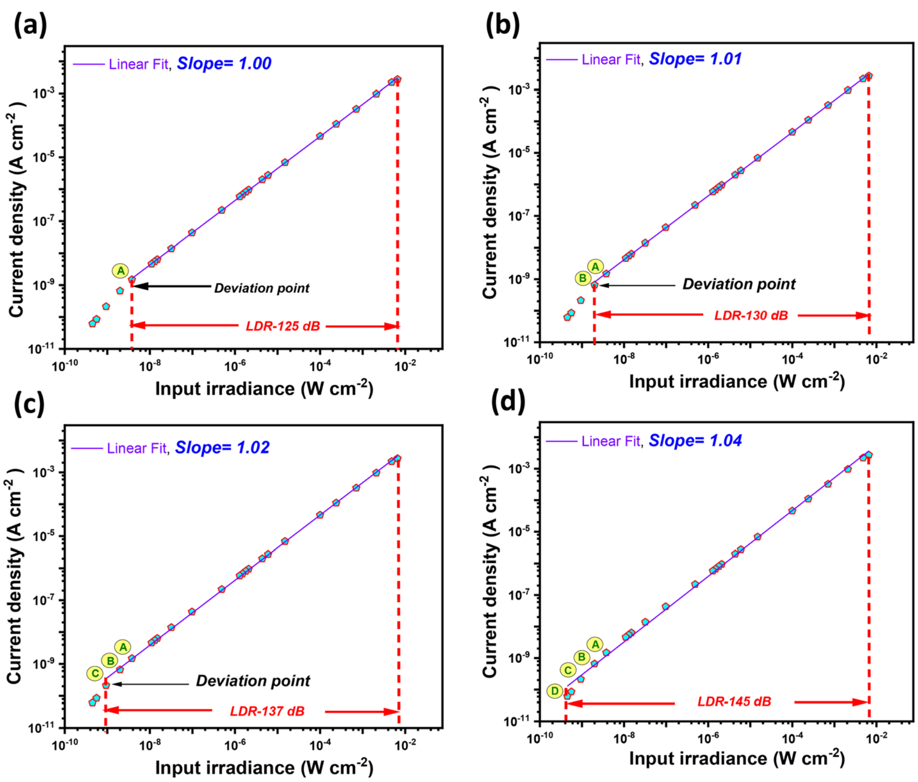

FIG. 2. Current density vs input irradiance plot of organic photodiode and the corresponding linear fit (solid line) with (a) slope = 1.00, (b) slope = 1.01, (c) slope = 1.02, and (d) slope = 1.04.

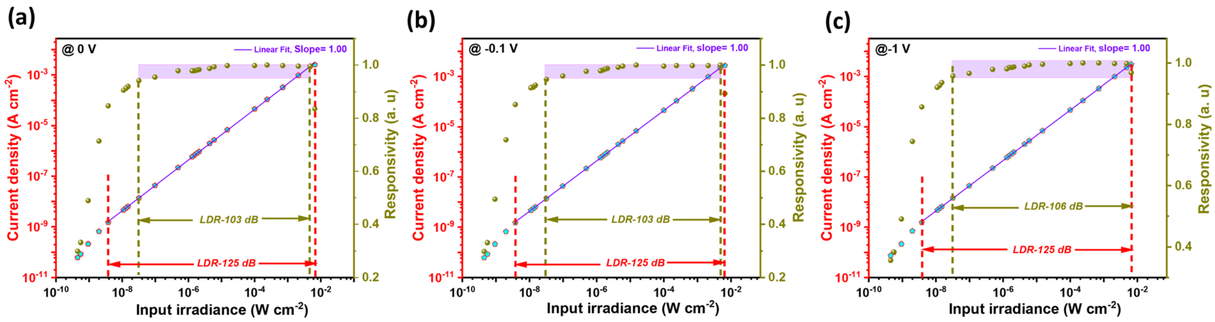

FIG. 3. LDR estimation using definition-1 (red color) and definition-2 (green color) at (a) 0 V, (b) −0.1 V, and (c) −1 V applied biases. The dotted lines represent the lower and upper limits of input irradiance contributing to the LDR.

the literature and from our measurement experience, the responsivity gradually decreases as the magnitude of light intensity decreases, typically dropping below the range that is convenient for experiments (μW to mW). In this scenario, the "constant value" range should have a well-defined boundary, such as <5% change from the maximum value (R_{max}), which can in turn be stated clearly in the reports. In this study, we have considered all data points, which are within the 5% variation from the maximum R value (or $R_{max} \times 95\%$) as "constant value" and derived the corresponding LDR. Figure 3(a) compares the LDR value using definition-1 and definition-2 at the self-powered mode (0 V). The R value is normalized to a maximum value of 1 in order to have a straight-forward comparison at different scenarios. If we strictly choose only the values that remain constant ($R_{max} \times 100\%$), the corresponding input light intensity range is 6×10^{-6}–5×10^{-3} W cm^{-2}, resulting in a LDR value of ∼60 dB only. However, considering the possible experimental uncertainty and other factors, we believe a 5% decline from the peak "R" value can be reasonably counted in the "constant value" regime and is represented using a colored box in the Fig. 3. In other words, data points, which maintain 95% of the peak value of R, is considered as a constant value. In this scenario, the L_{lower} value is shifted further to the lower range, 3.1×10^{-8} W cm^{-2}, and the resulting LDR value is ∼103 dB. However, for the case of definition-1, the deviation point is even further lower at 3.7×10^{-9} W cm^{-2}, resulting in a LDR value of 125 dB. From the comparison of LDR values using these two definitions, if the LDR value has to be similar for the diode studied here, the responsivity value that is >15% lower than the peak value has to be included in the "constant value" regime. The LDR value of definition-2 varies from 60 dB (strictly only constant values were counted) to 103 dB (data points with >95% of the maximum value) to 125 dB (data points with >85% of the maximum value) based on the way the "constant regime" is defined.

To further understand the influence of applied bias on the LDR, the measurements were carried out at −0.1 and −1 V, respectively, and results are plotted in Figs. 3(b) and 3(c), respectively. The major difference is specifically noticed at the highest illumination intensity data point (at 7×10^{-3} W cm^{-2}), wherein the R is ∼80% of the peak value at 0 V, 90% of the peak value at −0.1 V, and within the constant regime at −1 V. It is noted that the deviation from linearity or deviation from constant-value regime at higher intensity illumination is also potentially affecting the LDR value, but this report mainly focuses on the lower intensity region, as the existing measurement setup has limitation in increasing the light intensity beyond the range specified earlier. In general, the applied bias used in this study has relatively little effect on the LDR value since the deviation point at the lower light intensity region stays almost constant. Nevertheless, as the applied bias increases, the R gradually approaches the peak value at the highest irradiation intensity. It is also noteworthy that there is an increase in the J_d value of ∼2 orders of magnitude when the applied bias is increased from 0 to −1 V, but it does not having a considerable effect on the corresponding LDR value. Considering the J_d value as the lower limit of linearity is thus found not reliable in PDs. Overall, the difference in the LDR value when adopting definition-1 and definition-2 at different applied biases mainly depends on the way the "constant value" regime is considered or defined. The impacts of slope and various definitions on the LDR values of the system under study in this work are summarized in Fig. 4 and highlights the significance of standardizing the measurement and analysis protocol. We further emphasize that a comprehensive explanation of the sub-linear behavior of photoresponsivity at low-intensity input irradiation is still elusive, and future studies should concentrate on pinpointing the key factors contributing to this rather than arbitrarily assigning "trap-states" in general.

In addition to the aforementioned factors, a proper experimental setup and accurate measurement protocols are critical in obtaining reliable LDR values. As we measure low-level optical signals, the output is highly susceptible to errors due to random events and noise from various sources. For example, while considering the influence of traps in the low input light intensity region, in addition to recombination lifetime of the photogenerated carriers, experimental parameters such as lock-in time constant, chopper frequency, and applied bias should also be carefully considered.[23] For instance, a low chopper frequency and a long-time constant are effective in probing deeper traps with longer recombination times, limiting the decrease in photo response. The applied bias also plays a significant role, particularly when the corresponding field is strong enough to induce the detrapping process. Considering these potential factors underscores the importance of explicitly stating the experimental measurement parameters in the manuscript, ensuring a reliable basis for comparing reported values. Additionally, commonly used DC measurement techniques have the inherent limitation in identifying the signal of interest from noisy signals. Therefore, assessing such possible errors and using reliable detection techniques is crucial to ensure the reliability and repeatability of measured results. Regarding the detection techniques, the AC detection method using a mechanical light chopper and lock-in amplifier helps to improve the accuracy of the measured values.

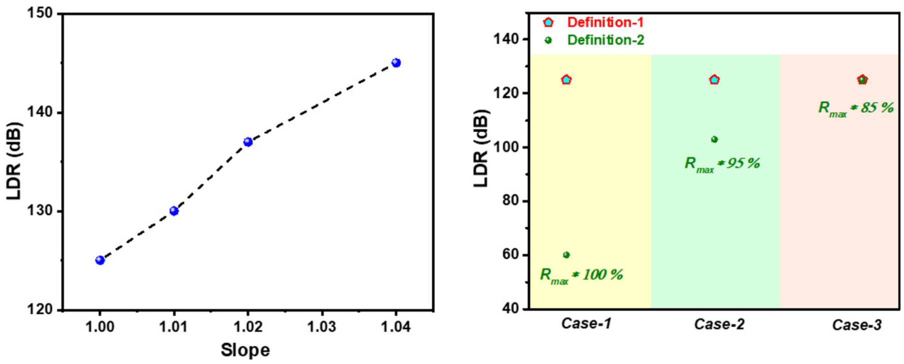

FIG. 4. Variation of LDR values in the studied organic photodiode due to (a) variation in slope from unity and (b) the adoption of different definitions.

This approach can minimize the error caused by fluctuations in incident light intensity (since the output of many light sources varies over time). Moreover, it can distinguish the desired signal buried in noise.[24,25]

In summary, we have emphasized the significance of requiring solid performance metric guidelines for determining the LDR of next-generation thin-film photodiodes. The importance of adhering to the unity slope in the double logarithmic plot of light intensity vs current density is demonstrated using a representative organic photodiode system. In addition, the importance of defining a boundary for the "constant responsivity" regime is crucial as it may potentially result in the misrepresentation of corresponding LDR values. The practice of counting the *NEP* as the lowest intensity limit led to inaccurate estimates of the LDR in all the systems investigated in this study, and clear examples in the literature show light intensity-dependent sublinear or superlinear photoresponsivity. Measuring the responsivity or photocurrent beyond the deviation point from linearity is recommended, and the measurement conditions and analysis preconditions should be clearly stated for enabling a reliable literature comparison.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Hrisheekesh Thachoth Chandran: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (supporting); Investigation (equal); Methodology (equal); Project administration (equal); Supervision (supporting); Writing – original draft (lead); Writing – review & editing (equal). **Sudhi Mahadevan:** Conceptualization (supporting); Data curation (supporting); Formal analysis (supporting); Investigation (supporting); Methodology (supporting); Writing – original draft (supporting); Writing – review & editing (supporting). **Ruijie Ma:** Data curation (supporting); Formal analysis (supporting); Investigation (supporting); Methodology (supporting); Writing – review & editing (supporting). **Yu Tang:** Data curation (equal); Investigation (equal); Methodology (equal). **Tao Zhu:** Data curation (supporting); Methodology (supporting). **Furong Zhu:** Data curation (supporting); Methodology (supporting). **Sai-Wing Tsang:** Data curation (supporting); Methodology (supporting); Writing – review & editing (supporting). **Gang Li:** Conceptualization (equal); Funding acquisition (lead); Methodology (equal); Project administration (equal); Supervision (lead); Writing – review & editing (equal).

DATA AVAILABILITY

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

REFERENCES

[1] T. Araki, K. Li, D. Suzuki, T. Abe, R. Kawabata, T. Uemura, S. Izumi, S. Tsuruta, N. Terasaki, and Y. Kawano, "Broadband photodetectors and imagers in stretchable electronics packaging," Adv. Mater. (published online 2023).
[2] G. Konstantatos, Nat. Commun. **9**, 5266 (2018).
[3] Z. Li, T. Yan, and X. Fang, Nat. Rev. Mater. **8**, 587–603 (2023).
[4] T. Yokota, P. Zalar, M. Kaltenbrunner, H. Jinno, N. Matsuhisa, H. Kitanosako, Y. Tachibana, W. Yukita, M. Koizumi, and T. Someya, Sci. Adv. **2**, e1501856 (2016).
[5] Z. Zhao, C. Xu, L. Niu, X. Zhang, and F. Zhang, Laser Photonics Rev. **14**, 2000262 (2020).
[6] H. Ren, J. D. Chen, Y. Q. Li, and J. X. Tang, Adv. Sci. **8**, 2002418 (2021).
[7] F. P. García de Arquer, A. Armin, P. Meredith, and E. H. Sargent, Nat. Rev. Mater. **2**, 16100 (2017).
[8] Z. Wang, Y. Tang, J. Han, and F. Zhu, Appl. Phys. Lett. **124**, 021103 (2024).
[9] C. Fuentes-Hernandez, W.-F. Chou, T. M. Khan, L. Diniz, J. Lukens, F. A. Larrain, V. A. Rodriguez-Toro, and B. Kippelen, Science **370**, 698 (2020).
[10] H. T. Chandran, H. Tang, T. Liu, S. Mahadevan, K. Liu, Z. Lu, J. Huang, Z. Ren, F. Liao, and Y. Chai, Mater. Horiz. **10**, 918 (2023).
[11] J. Kublitski, A. Hofacker, B. K. Boroujeni, J. Benduhn, V. C. Nikolis, C. Kaiser, D. Spoltore, H. Kleemann, A. Fischer, and F. Ellinger, Nat. Commun. **12**, 551 (2021).
[12] H. Thachoth Chandran, C. Yan, and G. Li, Adv. Energy Sustainability Res. **3**, 2200002 (2022).
[13] O. J. Sandberg, C. Kaiser, S. Zeiske, N. Zarrabi, S. Gielen, W. Maes, K. Vandewal, P. Meredith, and A. Armin, Nat. Photonics **17**, 368 (2023).
[14] Y. Fang, A. Armin, P. Meredith, and J. Huang, Nat. Photonics **13**(1), 1–4 (2019).
[15] J. Liu, M. Gao, J. Kim, Z. Zhou, D. S. Chung, H. Yin, and L. Ye, Mater. Today **51**, 475 (2021).
[16] J. Huang, J. Lee, J. Vollbrecht, V. V. Brus, A. L. Dixon, D. X. Cao, Z. Zhu, Z. Du, H. Wang, and K. Cho, Adv. Mater. **32**, 1906027 (2020).
[17] B. R. Sutherland, A. K. Johnston, A. H. Ip, J. Xu, V. Adinolfi, P. Kanjanaboos, and E. H. Sargent, ACS Photonics **2**, 1117 (2015).

[18]Y. Cheng, X. Liu, Z. Guan, M. Li, Z. Zeng, H. W. Li, S. W. Tsang, A. G. Aberle, and F. Lin, Adv. Mater. **33**, 2006170 (2021).
[19]T. Liu, Y. Foo, J. A. Zapien, M. Li, and S.-W. Tsang, Nat. Commun. **10**, 5089 (2019).
[20]D. Yang and D. Ma, Adv. Opt. Mater. **7**, 1800522 (2019).
[21]F. Wang, T. Zhang, R. Xie, Z. Wang, and W. Hu, Nat. Commun. **14**, 2224 (2023).
[22]Y. Park, C. Fuentes-Hernandez, K. Kim, W.-F. Chou, F. A. Larrain, S. Graham, O. N. Pierron, and B. Kippelen, Sci. Adv. **7**, eabj6565 (2021).
[23]L. Dou, J. You, Z. Hong, Z. Xu, G. Li, R. A. Street, and Y. Yang, Adv. Mater. **25**, 6642 (2013).
[24]S. Cova, A. Longoni, and I. Freitas, Rev. Sci. Instrum. **50**, 296 (1979).
[25]T. O'haver, J. Chem. Educ. **49**, A211 (1972).