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Organic Electronics to See Deeper and Go Farther: Recent Advances in Polymeric Devices for Infrared Sensing and Energy Storage

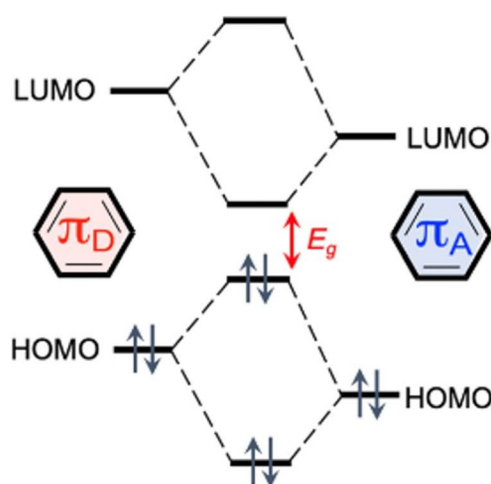
Tse Nga Ng¹

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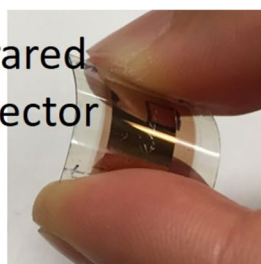
Abstract

This brief communication presents recent advances and emerging opportunities in narrow-bandgap polymeric devices for infrared sensing and energy storage applications. Donor–acceptor polymers with extended conjugation offer spectral tunability and redox stability, properties that are key to improving optoelectronic and electrochemical functions. The resulting devices and demonstrations highlight their potential to enable integrated energy and sensing in future autonomous systems.

Graphical Abstract



Infrared
detector



Energy
storage



Keywords Infrared photodetectors · retinomorph sensing · redox polymers · electrochemical energy storage

Introduction

The development of organic semiconductors has been part of the mobile electronic revolution, most visibly through their role in enabling portable, flexible displays. The global organic light-emitting diode (OLED) market is estimated

at approximately US \$50 billion in 2024,^{1,2} underscoring the economic value of these materials. Beyond displays, organic electronics offer a platform for innovations in bioelectronics,^{3–5} sensing technologies,^{6–8} and energy harvesting and storage systems^{9–11} due to their versatile electronic/mechanical tunability, scalability of organic films to cover large areas, and economical processing at low temperature through additive deposition.^{12–15} Because the breadth of potential applications is vast, ranging from health monitoring to sustainable energy solutions, it is not feasible to address all aspects within this brief communication. Instead,

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the following discussion will focus on two research directions within my research group, to present a perspective on the recent advances and emerging opportunities in narrow-bandgap polymeric devices for infrared sensing and energy storage applications, vital in future autonomous and connected systems.

A prominent class of narrow-bandgap polymers is designed with alternating donor and acceptor units within the polymer backbone. With this donor–acceptor (D–A) architecture, the chemical structures of unit moieties can be modularly adjusted to control the electronic hybridization of molecular orbitals, such as by varying electron-donating/withdrawing strength between intramolecular charge-transfer interactions.¹⁶ As a result, the electronic bandgap can be systematically reduced and is demonstrated to extend into shortwave and mid-infrared regions. Two examples pioneered by the Azoulay group^{17,18} are illustrated in Fig. 1a, and they have shown excellent performance in optoelectronic devices as well as redox energy storage cells. It is worth noting that these narrow-bandgap polymers are enhanced in electronic conductivity by the nature of D–A charge transfer and extended conjugation. The open-shell characteristics in

polymer #2 further improve its redox reversibility and stability.^{19,20} When combined with strategies to engineer mixed ionic–electronic conductivity,²¹ narrow-bandgap polymers are shown to be promising active electrode materials for electrochemical energy storage cells. With the multifunctional characteristics of these polymers, this report will first discuss their optical applications and then transition to their roles in electrochemical systems.

Polymeric Structures and Device Demonstrations for Infrared Detection

While most organic semiconductor devices function in the visible region, continual advances in molecular design are expanding their spectral response into the near- and mid-infrared regions, as presented in Fig. 1b. Conjugated D–A polymers have become a leading material platform in this context, generating photoresponse at $\sim 1.5 \mu\text{m}$. Their high oscillator strength, often exceeding that of inorganic semiconductors, enables strong absorption within thin films, as reflected in molar extinction coefficients above

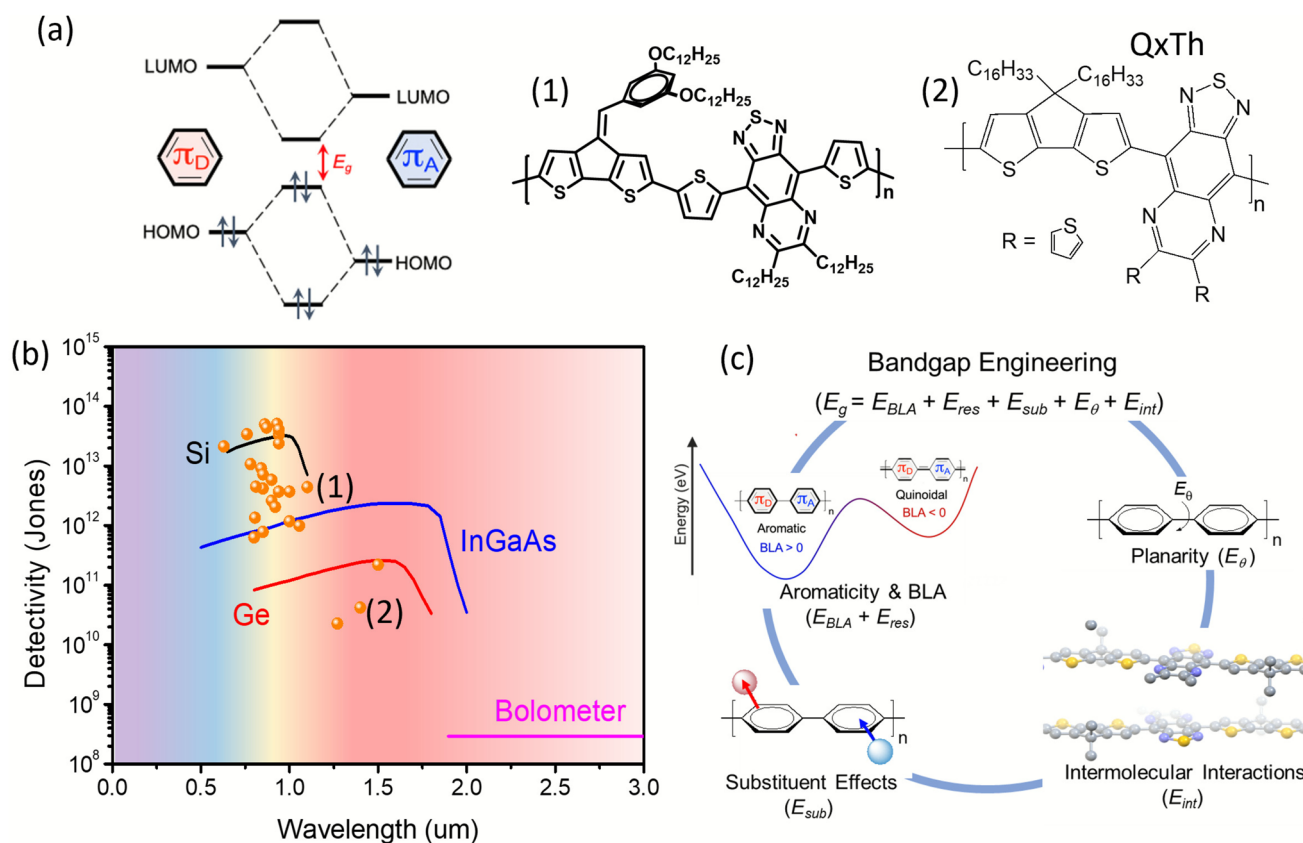


Fig. 1 (a) Hybridization of donor and acceptor units to systematically adjust the polymer bandgap. (b) Detectivity versus spectral wavelength of photodetectors. Orange circles represent various organic semiconductors. The labeled data (1), (2) are obtained using the poly-

mers shown in part (a). Reprinted with permission from Ref. 6, under the terms of the Creative Commons CC BY license. (c) Contributing factors that influence the bandgap of conjugated polymers. Reprinted with permission from Ref. 16.

$10^5 \text{ M}^{-1} \text{ cm}^{-1}$. Although the detectivity of organic detectors is currently lower than that of InGaAs, their scalability to large-area fabrication provides an advantage to realize large-format detectors, a capability that is difficult for epitaxial InGaAs to match.

To first order, the D-A building blocks control the electronic bandgap E_g , but other factors also exert a strong influence. Figure 1c illustrates key contributions including bond length alternation (BLA) along the conjugated backbone (E_{BLA}), torsional dihedral angle between D-A units (E_θ), resonance effects (E_{res}), electron-donating and withdrawing substituent effects (E_{sub}), and intermolecular interactions between chains (E_{int}). Smaller BLA values promote greater π -electron delocalization and a narrower E_g . Molecular design strategies such as introducing pro-aromatic or quinoial units, rigidifying the backbone to suppress torsional rotation, and employing noncovalent hydrogen bonding to lock in conformation have proven effective in increasing planarity and lowering E_g . Chemical substitution with electron-donating or withdrawing groups further tunes orbital energies.

Increased backbone planarity and stronger π - π stacking interactions promote greater π -electron delocalization, though often at the expense of solubility and ease of processing. Attaining narrow-bandgap polymers with high transduction efficiency remains an ongoing challenge, due to issues

with exciton dissociation and increasing recombination probability as the bandgap decreases.^{22,23} However, emerging design rules that link chemical structure, electronic interactions, and structural order to electronic correlation and energetic disorder are beginning to provide guiding principles, for example, for tuning of molecular structures and dielectric polarizability to enhance sensor detectivity.^{24–28} These insights are enabling rational design of conjugated polymers with extended infrared absorption and improved device performance.^{29,30}

In addition to optimizing individual devices, the integration of organic photodetectors with other circuit elements introduces new operating mechanisms that are not often used in conventional inorganic technologies, which are constrained by incompatibilities in heterogeneous integration processes. The compatibility with low-temperature processing made organic device integration relatively easy to implement. Demonstrations of integrated structures in Fig. 2 show the capabilities to achieve (a) filter-less spectral switching,^{31,32} (b) pixel-less imaging,^{33–35} and (c) motion-sensitive detection.^{36–38} These architectures provide the benefits of combining different functions and reducing footprints.

While the back-to-back diode configuration has typically been used for pixel addressing in array matrices,³⁹ this design is generalizable to other functions. Stacking two

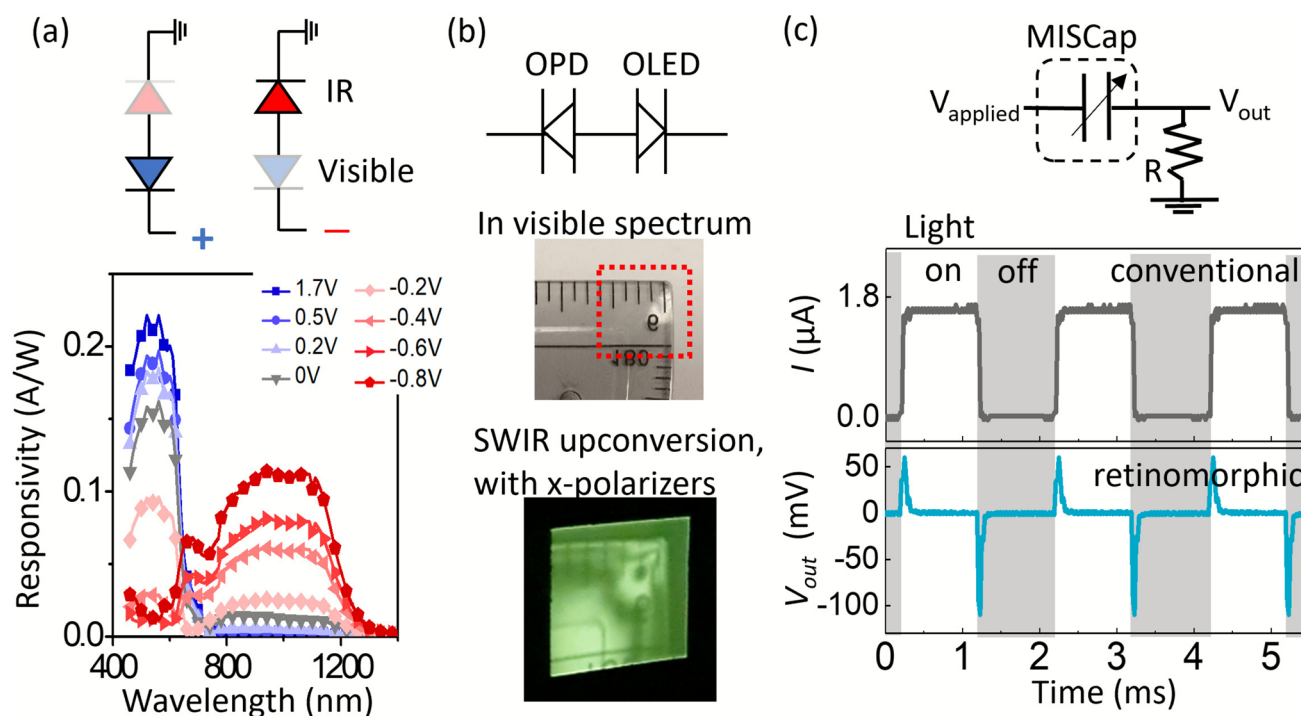


Fig. 2 (a) Back-to-back photodiodes to enable electrical switching of detection spectral range. Reprinted with permission from Ref. 31, under the terms of the Creative Commons CC BY license. (b) Back-to-back diode configuration integrating organic photodiode and organic light-emitting diode, to realize an electronic upconversion

imager. Adapted from Ref. 33 with permission from the Royal Society of Chemistry. (c) Motion-sensitive photodetection using high-pass RC filtering, to generate spiking response triggered by light intensity changes. Reprinted with permission from Ref. 36, under the terms of the Creative Commons CC BY license.

complementary photodiodes in tandem, the wavelength tunable detector³¹ in Fig. 2a switches between visible (400–700 nm) and infrared (700–1200 nm) modes depending on the bias polarity that controls the active diode for photodetection. The dual-band sensor provides spectral information without relying on external optical components such as filter wheels⁴⁰ or diffraction gratings, thereby reducing bulk and improving spectral scanning speed. Another back-to-back diode design incorporates an infrared organic photodiode (OPD) and an OLED to realize an electronic upconversion imager. In this case, photogenerated charges in the OPD are shuttled to the OLED layer locally with minimal lateral diffusion, so that only regions exposed to infrared light will induce OLED charge recombination and light emission, thus upconverting infrared absorption to a visible image. In conjunction with cross polarizers, the upconversion imager was demonstrated to visualize stress gradient in a plastic sample,³³ as seen in Fig. 2b.

With the growing demand for in-sensor processing and edge-computing, a class of organic retinomorphic devices^{36–38} has been developed to minimize data redundancy. By adding an insulator layer, a photodiode is modified into a light-sensitive metal–insulator–semiconductor capacitor (MISCap). The combination of MISCap and a resistor allows a more compact implementation to simplify event-driven circuits. In Fig. 2c, the RC (resistor–capacitor) high-pass filtering mechanism generates pulse signals only in response to dynamic changes but not for static illumination. This feature removes redundancy and delivers

streamlined data upon detecting motion, supporting low-power efficient data transfer. Compared to its photodiode counterpart, the retinomorphic sensor shows better detectivity and response speed due to the additional insulator dielectric, which reduces the dark current and the RC time constant.³⁶

Looking forward, the aforementioned advances open opportunities for integrating organic sensors with neuromorphic processors to enable real-time machine learning for navigation, imaging, and diagnostic applications. As autonomous sensing platforms require compact and efficient power supplies, we next examine the potential of narrow-bandgap polymers in energy storage devices to meet the energy demands of integrated sensing systems.

Conjugated Redox Polymers and Electrochemical Devices for Energy Storage

Organic redox polymers have a long history in electrochemical energy storage cells (EES), having been incorporated into batteries and supercapacitors. Narrow-bandgap D-A polymers belong to the class of redox polymers where the redox-active sites are integrated in the conjugated backbone (Fig. 3b), in contrast to being tethered as pendant groups on non-conjugated polymer chains (Fig. 3a). Embedding redox groups within the conjugated framework helps to stabilize charged states and thereby extend the electrochemical

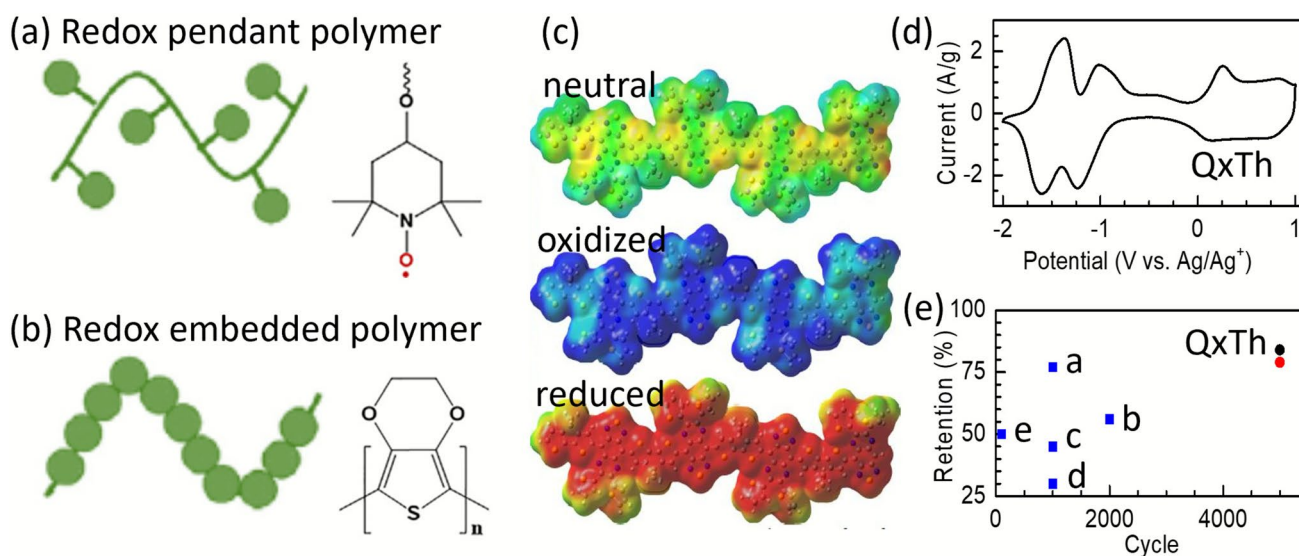


Fig. 3 (a) Redox-active groups attached as pendants to a non-conjugated polymer backbone. (b) Redox-active groups embedded in the polymer backbone. Adapted with permission from Ref. 41. (c) Electrostatic potential map of the conjugated polymer (2) QxTh in Fig. 1a. The blue and red color represents the highest (fewer electrons) and

lowest (more electrons) electrostatic potential, respectively. (d) Cyclic voltammetry at a scan rate of 10 mV/s. (e) Capacitance retention for n-type Faradaic polymers. Parts (c) and (d) are reprinted with permission from Ref. 19.

reversibility and cycle life of the polymers.⁴¹ In particular, D-A polymers with open-shell characteristics, arising from strong π -electron correlations and extensive delocalization (Fig. 3c), exhibit high electrical conductivity and stability across a wide potential window of 3 V, such as the QxTh polymer¹⁹ example in Figs. 1a and 3d. The energy density of an EES device follows $E = CV^2/2$, which is linearly dependent on the specific capacitance C and proportional to the square of the operating voltage window V . Thus, by doubling the operating voltage through the D-A polymer QxTh, the cell energy density is quadrupled. Furthermore, QxTh also demonstrates excellent cycle life, retaining 85% of its initial capacitance after 5000 full charge–discharge cycles, surpassing the stability of other n-type redox polymers^{42–45} in Fig. 3e.

In addition to modifying the electrodes with redox-active polymers, another key component in EES cells is the electrolyte,^{46,49} which maintains charge balance and influences electrode stability. In a hybrid metal ion cell, where zinc is used as the anode and polyaniline (PANI) polymer as the cathode, the inclusion of a protic additive in the electrolyte is shown to be essential for PANI operation in nonaqueous electrolytes. Without such stabilization, the redox activity of polyaniline is hindered by the instability of pernigraniline salt (PS), which degrades into oligo-aniline. Incorporating propylene glycol as a protic additive leverages hydrogen bonding interactions to stabilize the PS form of PANI,

thereby promoting reversible redox reactions. This strategy⁴⁶ mitigates capacity fading, improves PANI utilization, and extends cycling lifetime as displayed in Fig. 4a.

The cycle life of EES cells is an important consideration for applications in remote locations that are hard to reach for maintenance. Although the energy densities of zinc-carbon ion capacitors (ZIC) are lower than their lithium and sodium counterparts per discharge cycle, because of the excellent cycling stability enabled by suitable electrolytes,^{47,50} the cumulative capacities of ZICs over its lifetime can be far higher than lithium and sodium ion capacitors^{51–53} in Fig. 4b. In addition, zinc offers advantages of lower flammability and improved safety. These attributes make ZICs very attractive as power sources for autonomous electronics and Internet-of-Things applications, where extended cycle life is essential to minimize maintenance costs and avoid frequent battery replacements. This advantage becomes even more compelling in large-scale sensor networks comprising millions of nodes, where the logistical and economic burden of routine battery replacement would otherwise be unsustainable.

Beyond stability, another advantage of D-A redox polymers is their compatibility for integration into multifunctional composites.^{54–56} One approach to boost storage capacity is to exploit structural volume by developing structural batteries or supercapacitors, where energy storage is integrated with load-bearing functions, thereby

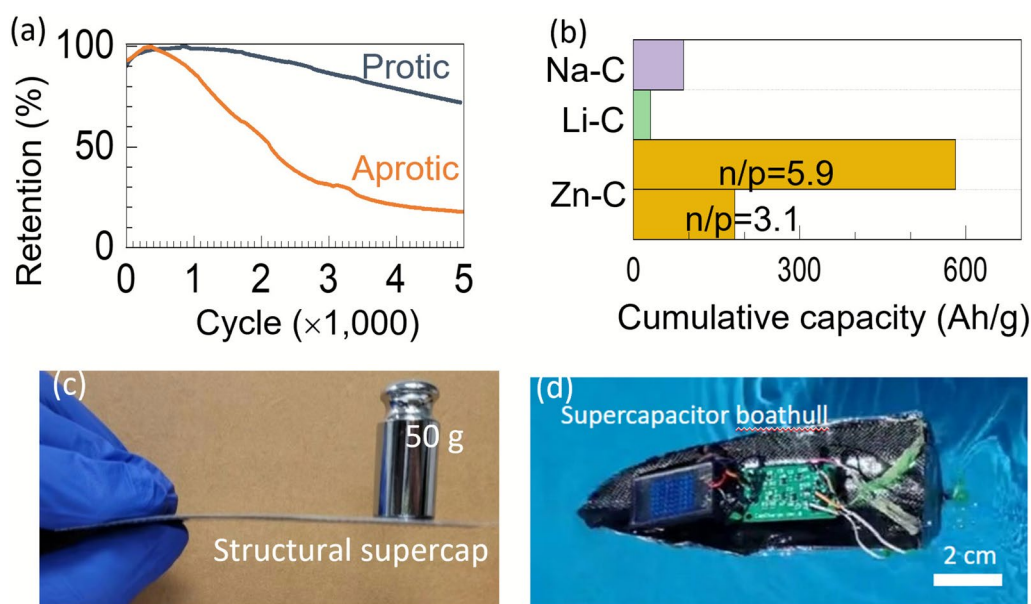


Fig. 4 (a) Capacitance retention of Zn-PANI supercapacitors using protic versus aprotic electrolyte. Reprinted with permission from Ref. 46, under the terms of the Creative Commons CC BY license. (b) Gravimetric cumulative capacities of metal ion capacitors. Reprinted with permission from Ref. 47, under the terms of the Creative Commons CC BY license. (c) Photograph of a structural supercapacitor

laminated supporting a 50-g weight with minimal deflection. (d) Demonstration of a boat model in which the boat hull is a multifunctional supercapacitor charged by the solar cell to drive the boat motor. Parts (c) and (d) are reprinted with permission from Ref. 48, under the terms of the Creative Commons CC BY license.

reducing overall mass and weight. Carbon fibers, commonly used in structural composites, are also electrically conductive and can serve as electrode scaffolds when combined with redox polymers. By stacking these modified electrodes with separators and/or solid-state electrolytes, complete electrochemical cells can be assembled in a laminate architecture that offers mechanical strength and electrochemical energy storage. Such multifunctional designs are attractive for aerospace and maritime structures, where carbon–fiber composites are already widely deployed. As shown in Fig. 4c, a prototype multifunctional supercapacitor supported a 50-g weight while delivering energy density of 57.5 mWh/kg at power density of 1 kW/kg.⁴⁸ Inspired by the prevalent use of carbon–fiber laminates in boat construction, we fabricated a model boat whose hull was composed entirely of structural supercapacitors, serving dual functions of structural support and energy storage for powering the boat motor in Fig. 4d. Coupled with a solar cell as the sole energy input, the system demonstrated 1.9 min of motor run time after 4.8 min of charging under mid-afternoon sunlight. This demonstration highlights the potential of using redox polymers to meet the structural and energy storage demands in an autonomous energy-harvesting system.

Conclusions

In summary, narrow-bandgap polymers provide a versatile platform that presents new opportunities in optoelectronic and electrochemical applications. For the D-A conjugated polymers, many structure–property–function relationships remain unexplored, challenging researchers to understand the material processing and device physics to improve performance. Nonetheless, in optoelectronics, the material tunability has extended the absorption spectrum into the near- and mid-infrared, enabling scalable detectors and in-sensor processing. The tunable spectral range can add new capabilities to improve optical diagnostics, and economical fabrication can lead to unexpected applications, analogous to how low-cost mobile cameras has become a ubiquitous tool in our lives. Moreover, the extended π -conjugation that narrows the polymer bandgap also stabilizes redox states in energy storage, delivering exceptional electrochemical reversibility and cycle life, making these materials promising for future energy-autonomous systems.

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Conflict of interest The author has no conflict of interest to declare.

References

1. Roots analysis <https://www.rootsanalysis.com/oled-market> (2025)
2. Expert market research <https://www.expertmarketresearch.com/reports/oled-market> (2025)
3. S. Inal, J. Rivnay, A.-O. Suiu, G.G. Malliaras, and I. McCulloch, *Acc. Chem. Res.* 51, 1368 (2018).
4. G. Malliaras, and I. McCulloch, *Chem. Rev.* 122, 4323 (2022).
5. J. Liu, M. Verrett, A. Wieand, A. Burch, A. Jeon, J. Collins, C. Yalcin, H. Garudadri, A.J. Skalsky, and T.N. Ng, *Biosens. Bioelectron.* 267, 116829 (2025).
6. V. Pecunia, L. Petti, J. Andrews, R. Olleiro, G. H. Gelinck, B. Nasrollahi, J. M. Jailani, N. Li, J. H. Kim, T. N. Ng, H. Feng, Z. Chen, Y. Guo, L. Shen, E. Lhuillier, L. Kuo, V. K. Sangwan, M. C. Hersam, B. Fraboni, L. Basirico, A. Ciavatti, H. Wu, G. Niu, J. Tang, G. Yang, D. Kim, D. Dremann, O. Jurchescu, D. Bederak, A. Shugla, P. Costa, N. Perinka, S. Lanceros-Mendez, A. Chortos, S. Khuje, J. Yu, S. Ren, A. Mascia, M. Concas, P. Cosseddu, R. J. Young, T. Yokota, T. Somoya, S. J. Jeon, N. Zhaon, Y. Li, D. Shukla, S. Wu, Y. Zhu, K. Takei, Y. Huang, J. Spiece, P. Gehring, K. Persaud, E. Llobet, S. Krik, S. Vasquez, M. Aurora Costa Angeli, P. Lugli, B. Fabbri, E. Spagnoli, A. Rossi, L. G. Occhipinti, C. Tang, W. Yi, D. Ravenscroft, T. R. Kandukuri, Z. Ul Abideen, Z. Azimi, A. Tricoli, A. Rivadeneyra, S. Rojas, A. Gaiardo, M. Valt, V. Galstyan, D. Zappa, E. Comini, V. Noel, G. Mattana, B. Piro, E. Strand, E. Bihar, G. L. Whiting, B. Shkodra, M. Petrelli, G. Moro, A. Ruccci, A. Miglione, S. Cinti, A. J. Casson, Z. Wang, D. Bird, J. C. Batchelor, L. Xing, L. S. J. Johnson, A. A. Alwatter, A. Kyndiah, F. A. Viola, M. Caironi, F. M. Albarghouthi, B. N. Smith, A. D. Franklin, A. Pal, K. Banerjee, Z. T. Johnson, J. C. Claussen, A. Moudgil, and W. L. Leong, *Nano Futures* 8, 032001 (2024)
7. S. Wu, L. Yao, A. Shiller, A.H. Barnard, and J.D. Azoulay, *Adv. Electron Mater.* 7, 2100223 (2021).
8. S. Yu, X. Sun, Z. Yu, J. Jung, S. Ishii, C.T. Hayes, V.C. Pierre, A.H. Flood, J.D. Azoulay, and T.N. Ng, *Mater. Horiz.* 12, 6784 (2025).
9. S. Shoaee, H.M. Luong, J. Song, Y. Zou, T.Q. Nguyen, and D. Neher, *Adv. Mater.* 36, 2302005 (2024).
10. D.G. Mackanic, T.H. Chang, Z. Huang, Y. Cui, and Z. Bao, *Chem. Soc. Rev.* 49, 4466 (2020).
11. T.P. Nguyen, A.D. Easley, N. Kang, S. Khan, S.M. Lim, Y.H. Rezenom, S. Wang, D.K. Tran, J. Fan, R.A. Letteri, X. He, L. Su, C.H. Yu, J.L. Lutkenhaus, and K.L. Wooley, *Nature* 593, 61 (2021).
12. S. Ready, F. Endicott, G. Whiting, T. N. Ng, E. Chow, and J.-P. Lu, *NIP & Digital Fabrication Conference* 1, 9 (2013)
13. T.N. Ng, D.E. Schwartz, P. Mei, B. Krusor, S. Kor, J. Veres, P. Bröms, T. Eriksson, Y. Wang, O. Hagel, and C. Karlsson, *Sci. Rep.* 5, 13457 (2015).
14. K. Kwon, and T.N. Ng, *Org. Electron.* 15, 294 (2014).
15. M.K. Rahman, T.H. Phung, S. Oh, S.H. Kim, T.N. Ng, and K.S. Kwon, *ACS Appl. Mater. Interfaces* 13, 18227 (2021).
16. N. Li, P. Mahalingam, J.H. Vella, D.-S.S. Leem, J.D. Azoulay, and T.N. Ng, *Mater. Sci. Eng. R-Rep.* 146, 100643 (2021).
17. D.B. Sulas, A.E. London, L. Huang, L. Xu, Z. Wu, T.N. Ng, B.M. Wong, C.W. Schlenker, J.D. Azoulay, and M.Y. Sfeir, *Adv. Opt. Mater.* 6, 1701138 (2018).
18. J.H. Vella, L. Huang, N. Eedugurala, K. Mayer, T.N. Ng, and J. Azoulay, *Sci. Adv.* 7(24), abg2418 (2021).
19. K. Wang, L. Huang, N. Eedugurala, S. Zhang, M.A. Sabuj, N. Rai, X. Gu, J.D. Azoulay, and T.N. Ng, *Adv. Energy Mater.* 9(47), 1902806 (2019).

20. L. Yao, J. Liu, N. Eedugurala, P. Mahalingavelar, D.J. Adams, K. Wang, K.S. Mayer, J.D. Azoulay, and T.N. Ng, *Cell Rep. Phys. Sci.* 3(3), 100792 (2022). <https://doi.org/10.1016/j.xcrp.2022.100792>.
21. L. Zhao, Q. Dong, R. Yi, H. Shao, Y. Shen, and L. Chen, *CCS Chem.* 7, 22 (2025). <https://doi.org/10.31635/ccschem.024.202404284>.
22. Z. Wu, W. Yao, A.E. London, J.D. Azoulay, and T.N. Ng, *Adv. Funct. Mater.* 28, 1800391 (2018).
23. J. Benduhn, K. Tvingstedt, F. Piersimoni, S. Ullbrich, Y. Fan, M. Tropiano, K.A. McGarry, O. Zeika, M.K. Riede, C.J. Douglas, S. Barlow, S.R. Marder, D. Neher, D. Spoltore, and K. Vandewal, *Nat. Energy* 2, 17053 (2017).
24. P. Jacoutot, A.D. Scaccabarozzi, D. Nodari, J. Panidi, Z. Qiao, A. Schiza, A.D. Nega, A. Dimitrakopoulou-Strauss, V.G. Gregoriou, M. Heeney, C.L. Chochos, A.A. Bakulin, and N. Gasparini, *Sci. Adv.* 9, eadh2694 (2023).
25. Z. Wu, N. Li, N. Eedugurala, J.D. Azoulay, D.-S. Leem, and T.N. Ng, *Npj Flex Electron.* 4, 6 (2020).
26. Y. Chen, Y. Zheng, J. Wang, X. Zhao, G. Liu, Y. Lin, Y. Yang, L. Wang, Z. Tang, Y. Wang, Y. Fang, W. Zhang, and X. Zhu, *Sci. Adv.* 10, eadm9631 (2024).
27. Z. Wu, Y. Zhai, W. Yao, N. Eedugurala, S. Zhang, L. Huang, X. Gu, J.D. Azoulay, and T.N. Ng, *Adv. Funct. Mater.* 28, 1805738 (2018).
28. T. Bills, C.T. Liu, J. Lim, N. Eedugurala, P. Mahalingavelar, B. Seo, E.T. Hanna, T.N. Ng, and J.D. Azoulay, *Adv. Funct. Mater.* 34, 2314210 (2024).
29. B. Seo, J. Chung, N. Eedugurala, J.D. Azoulay, H.J. Kim, and T.N. Ng, *ACS Appl. Electron. Mater.* 5, 6401 (2023).
30. N. Li, J. Lim, J.D. Azoulay, and T.N. Ng, *J Mater Chem C Mater* 8, 15142 (2020).
31. N. Li, N. Eedugurala, J.D. Azoulay, and T.N. Ng, *Cell Rep Phys Sci* 3, 100711 (2022).
32. Z. Lan, and F. Zhu, *ACS Nano* 15, 13674 (2021).
33. C. Shin, N. Li, B. Seo, N. Eedugurala, J.D. Azoulay, and T.N. Ng, *Mater. Horiz.* 9, 2172 (2022).
34. C.-J. Shih, Y.-C. Huang, T.-Y. Wang, C.-W. Yu, I.-S. Hsu, A. Khalik Akbar, J.-Y. Lin, S. Biring, J.-H. Lee, and S.-W. Liu, *Sci. Adv.* 9, eadd7526 (2023).
35. W. Yao, Z. Wu, E. Huang, L. Huang, A.E. London, Z. Liu, J.D. Azoulay, and T.N. Ng, *ACS Appl. Electron. Mater.* 1, 660 (2019).
36. S.E. Wu, L. Zeng, Y. Zhai, C. Shin, N. Eedugurala, J.D. Azoulay, and T.N. Ng, *Adv. Sci.* 10(31), 2304688 (2023).
37. C. Trujillo Herrera, and J.G. Labram, *ACS Appl. Electron. Mater.* 4, 92 (2022).
38. X. Zhang, and J.G. Labram, *J. Mater. Chem. C Mater.* 10, 12998 (2022).
39. H.C. Ko, M.P. Stoykovich, J. Song, V. Malyarchuk, W.M. Choi, C.J. Yu, J.B. Geddes, J. Xiao, S. Wang, Y. Huang, and J.A. Rogers, *Nature* 454, 748 (2008).
40. W. Kim, S.K. Kim, S. Jeon, J. Ahn, B.K. Jung, S.Y. Lee, C. Shin, T.Y. Seong, S. Jeong, H.S. Jang, Ts.N. Ng, and S.J. Oh, *Adv. Funct. Mater.* 32, 2111409 (2022).
41. J. Kim, J.H. Kim, and K. Ariga, *Joule* 1, 739 (2017).
42. H. Zhang, M. Yao, J. Wei, Y. Zhang, S. Zhang, Y. Gao, J. Li, P. Lu, B. Yang, and Y. Ma, *Adv. Energy Mater.* 7, 1701063 (2017).
43. X. Ju, L. Kong, J. Zhao, and G. Bai, *Electrochim. Acta* 238, 36 (2017).
44. P.M. Dicarmine, T.B. Schon, T.M. McCormick, P.P. Klein, and D.S. Seferos, *J. Phys. Chem. C* 118, 8295 (2014).
45. L.A. Estrada, D.Y. Liu, D.H. Salazar, A.L. Dyer, and J.R. Reynolds, *Macromolecules* 45, 8211 (2012).
46. C. Shin, E.H. Lee, H.J. Eun, J. Jung, J.H. Kim, and T.N. Ng, *Small Sci.* 4, 2400295 (2024).
47. C. Shin, L. Yao, S.-Y. Jeong, and T.N. Ng, *Sci. Adv.* 10, eadf9951 (2024).
48. L. Yao, K. Zheng, N. Koripally, N. Eedugurala, J.D. Azoulay, X. Zhang, and T.N. Ng, *Sci. Adv.* 9, eadh0069 (2023).
49. C. Shin, L. Yao, H. Lin, P. Liu, and T.N. Ng, *ACS Energy Lett.* 8(4), 1911 (2023).
50. L. Yao, N. Koripally, C. Shin, A. Mu, Z. Chen, K. Wang, and T.N. Ng, *Nat. Commun.* 16, 3597 (2025).
51. Y. Zhang, J. Jiang, Y. An, L. Wu, H. Dou, J. Zhang, Y. Zhang, S. Wu, M. Dong, X. Zhang, and Z. Guo, *ChemSuschem* 13, 2522 (2020).
52. R. Thangavel, B.K. Ganesan, V. Thangavel, W.S. Yoon, and Y.S. Lee, *ACS Appl. Energy Mater.* 4, 13376 (2021).
53. L. Li, D. Zhang, Y. Gou, J. Fang, Q. Kang, R. Feng, Z. Liang, and J. Deng, *J. Energy Storage* 40, 102822 (2021).
54. L.E. Asp, M. Johansson, G. Lindbergh, J. Xu, and D. Zenkert, *Funct. Compos. Struct.* 1, 42001 (2019).
55. L.E. Asp, K. Bouton, D. Carlstedt, S. Duan, R. Harnden, W. Johansson, M. Johansen, M.K.G. Johansson, G. Lindbergh, F. Liu, K. Peuvot, L.M. Schneider, J. Xu, and D. Zenkert, *Adv. Energy Sustain. Res.* 2, 2000093 (2021).
56. T. Zhou, E. Dickinson, J.G. Boyd, J.L. Lutkenhaus, and D.C. Lagoudas, *Multifunct. Mater.* 3, 44002 (2021).

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