D-A-\(\pi\)-A Motif Quinoxaline-Based Sensitizers with High Molar Extinction Coefficient for Quasi-Solid State Dye-sensitized Solar Cells

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**ABSTRACT:** To meet the requirement of high molar extinction coefficient, broaden absorption spectrum and photo/thermal stable for sensitizers of quasi-solid dye-sensitized solar cells (Qs-DSSCs) with reduced film thickness, a novel D-A-\(\pi\)-A configuration organic sensitizer \(\text{IQ22}\) was specifically designed, in which the conjugation bridge of cyclopentadithiophene (CPDT) unit was incorporated to widen the light response and enhance molar coefficients for increasing the short-circuit current density \((J_{SC})\), and the octane chain on CPDT was targeted for suppressing the charge recombination and improving the open-circuit voltage \((V_{OC})\). As a result, the Qs-DSSC based on
IQ22 exhibits very promising conversion efficiency as high as 8.76%, with a $J_{SC}$ of 18.19 mA cm$^{-2}$, a $V_{OC}$ of 715 mV, and a fill factor (FF) of 0.67 under AM 1.5 illumination (100 mW cm$^{-2}$), standing out in the Qs-DSSCs utilizing metal-free organic sensitizers.

**Keywords:** quinoxaline, auxiliary acceptors, sensitizer, quasi-solid state, dye-sensitized solar cells

**INTRODUCTION**

In the fields of dye-sensitized, perovskite and other emerging solar cell technologies, stability issue on cell devices is recognized as an urgent problem for a new generation of practical photovoltaic devices. Although perovskite solar cells can show efficiency of more than 20%, the superiority in environmental friendliness and stability of DSSCs can be more attractive for some applications.$^{6}$ Accordingly, for low-cost, high-efficiency dye-sensitized solar cells (DSSCs), the development of acceptably stable quasi-solid-state or solid-state devices, without any volatile electrolyte solution, is critical at present. Due to facile diffusion in porous TiO$_2$ and the large area contact with counter electrode, the quasi-solid state dye-sensitized solar cell (Qs-DSSC) is not only conducive to a high power conversion efficiency (PCE),$^{7-8}$ but also can significantly improve the device stability, thereby becoming a hot topic in the DSSCs field. Moreover, polymer gel electrolytes have led to efficient quasi-solid electrolytes for Qs-DSSCs.$^{9-10}$

Currently, the main practical limitations for the evolution of Qs-DSSCs are lower power conversion efficiency (PCE) arising from low electrolyte ion diffusion rates and the resulting serious electronic recombination.$^{11-15}$ In this regard, Qs-DSSCs always need thin TiO$_2$ electrode, and accordingly an ideal sensitizer should exhibit strong light-harvesting capability. Indeed, the desirable sensitizer with high molar extinction coefficient and broaden light response region is very critical to the thinner TiO$_2$ electrode-based Qs-DSSCs, in which the electronic recombination
can be distinctly repressed, and the intramolecular charge transfer (ICT) can be optimized. Recently, a new generation of D-A-π-A motif organic sensitizers came into existence with an auxiliary acceptor group introduced into the π-bridge of the D-π-A framework, leading to excellent photovoltaic performances. As an exemplary D-A-π-A featured dye with quinoxaline as additional unit, IQ4 showed high PCE of 9.24% with volatile iodine electrolyte. Herein we focused on how to increase molar extinction coefficients and broaden light-responsive region, thereby specifically developing targeted sensitizers for constructing high performance Qs-DSSCs.

Scheme 1. a) The molecular structures of IQ22 and IQ4 and b) their calculated energy-level diagram and major electron-transfer absorption processes.

Based on IQ4, we report a new D-A-π-A DSSC sensitizer IQ22 (shown in Scheme 1), in which the conjugation bridge of cyclopentadithiophene (CPDT) unit was incorporated to widen the light response and enhance molar coefficients for increasing the short-circuit current density ($J_{SC}$), the octane chain on CPDT was targeted for suppressing the reverse current and improving the open-circuit voltage ($V_{OC}$). As demonstrated, a commercial I$_{3}^{-}$/I$_{3}^{-}$ polymer gel electrolyte OPV-
MPV-I was successfully exploited for fabricating Qs-DSSCs utilizing \textbf{IQ22} and \textbf{IQ4} as sensitizers, achieving high conversion efficiencies of 8.76\% and 8.30\% under 100 mW cm\(^{-2}\) illumination, respectively, which is an exhilarating PCE for Qs-DSSCs based on metal-free organic sensitizers. Furthermore, these devices showed excellent stability, almost maintaining the initial conversion efficiency even after 1000 h.

\textbf{RESULTS AND DISCUSSION}

\textbf{Charge Transport Difference between Gel and Volatile Electrolytes.} In order to quantify any bottleneck limiting the efficiency for Qs-DSSCs, we first performed conductivity (\(\sigma\)) measurements of gel and volatile electrolytes (See experimental section) with electrochemical impedance spectroscopy. \(^{28}\) This offers key information about the mobility of the ions, their interaction with the solvent and any ion-pairing phenomena. As shown in Figure 1a, all plots of \(\ln \sigma\) against 1000/T give straight lines, which is typical ion-conducting behavior follow an Arrhenius relationship. \(^{29}\) In Figure 1a, the obvious difference between the gel and volatile electrolyte is the variation of the slope with measurement temperature. With increasing temperature, the conductivity of the gel electrolyte rises rapidly owing to the viscosity reduction, whereas the change for the volatile electrolyte shows a more gradual process. At room temperature, the conductivity of the gel and volatile electrolyte are 2.10 \(\times\) 10\(^{-3}\) S cm\(^{-1}\) and 3.0 \(\times\) 10\(^{-3}\) S cm\(^{-1}\), respectively. In addition, Tafel polarization measurements were implemented using dummy cells with each of the different electrolytes between two Pt electrodes (Figure 1b). \(^{30\text{-}31}\) In the Tafel and diffusion zone, the exchange current density (\(J_0\)) and limiting diffusion current density (\(J_{\text{lim}}\)) values lie in the order of volatile > gel for \textbf{IQ22} and \textbf{IQ4}, respectively, indicating that the gel electrolyte has some limitations in the charge-transfer and diffusion likely due to the greater viscosity. \(^{32}\) As
shown in Table 1 however, the change of electrolyte did not cause a significant impact on the short-circuit current density ($J_{SC}$) for IQ22 or IQ4.

**Figure 1.** Temperature dependence of ionic conductivity (a) and Tafel polarization curves of symmetric dummy cells with two platinum electrodes at room temperature (b) for volatile and gel electrolytes.

**Enhancement in Molar Extinction Coefficients and Light-Harvesting Capability.** In DSSCs, the sensitizers with high extinction coefficients allow reduced thickness of TiO$_2$ electrode, which results in increase of the average optical power density within the film and decrease of the charge recombination sites, as the film becomes thicker the charges have more chance of recombining before influencing the potential at the electrodes. $^{33}$ Recently, a D-A-$\pi$-A prototype has become attractive, especially for constructing high extinction coefficients, broaden light response, and photo/thermal stable organic sensitizing dyes. $^{34-35}$ As shown in Scheme 1, for the design of sensitizer IQ22, we employed indoline as the electron donor since it manifested superior electron-donating capacity and led to excellent photovoltaic performance in a number of efficient D-A-$\pi$-A sensitizers. $^{36-38}$ We also used the standard group cyanoacetic acid as the acceptor/anchor unit. For an ideal sensitizer, high molecular extinction coefficient and broad wavelength response are highly preferable for high-efficiency DSSCs. On the basis of the rational molecular design, the
structure modification in this report was conducted by introducing the high conjugation building block of CPDT as π bridge (IQ22), instead of the thiophene unit (IQ4). In particular, dye IQ22 exhibits appropriate photo-physical properties, such as a higher molecular extinction coefficient and broad light response region. The addition of two methoxy groups in the auxiliary (quinoxaline) unit can fine-tune and optimize the \( E_{\text{OX}} \) (The first oxidation potential) and \( E_{\text{RED}}^* \) (The excited-state reduction potential), through certain electron-donating character. In addition, octyl groups were grafted onto the CPDT unit to reduce aggregation and to address the serious electronic recombination in Qs-DSSCs.\textsuperscript{11-15} The synthetic route is presented in Figure S1.

\textbf{Figure 2}. Absorption spectra of IQ22 and the reference dye IQ4. a) The experimental spectra (in CH\(_2\)Cl\(_2\)) are shown as continuous lines and the theoretical electronic transitions are shown as bars for both IQ22 (red) and IQ4 (black). Theoretical data were computed using TD-DFT (CH\(_2\)Cl\(_2\)) and b) The experimental spectra on 4 μm TiO\(_2\) thin film.

**Experimental and Calculated Absorption Properties.** To preliminarily estimate the effect of structure modification on the light-harvesting capacity for IQ22, we tested the UV-Vis absorption spectra of the two dyes in CH\(_2\)Cl\(_2\) (Figure 2a) and their corresponding data are summarized in Table 1. Both dyes show two distinct absorption bands at about 325 and 540 nm, corresponding to the \( \pi-\pi^* \) and ICT bands, respectively. With respect to IQ4, IQ22 presents a notable bathochromic
shift in the maximum visible absorption wavelength from 531 to 555 nm, which arises from the introduction of a large π-linker CPDT unit. As expected, replacing the thiophene unit (in IQ4) with CPDT (in IQ22) is beneficial for greatly enhancing the molar extinction coefficient (up to 63200 M\(^{-1}\) cm\(^{-1}\), 2.47-fold greater than that of the reference dye IQ4) and light-harvesting with red shift in absorption band, which are the preconditions for obtaining a high photocurrent output. Upon loading on TiO\(_2\) films (Figure 2b), both dyes show hypsochromic shift from 531 to 497 nm for IQ4 and from 555 to 516 nm for IQ22, due to the deprotonation of the cyanoacetic acid group. Obviously, IQ22 shows a higher and broader spectrum in the visible region relative to IQ4. On the other hand, the broader peak width on the films indicate that aggregation inevitably occurs to some extent in these films for both dyes. The high molar extinction coefficient and wide absorption spectrum for IQ22 exactly cater to the reduced film thickness requirements of Qs-DSSCs since the charge recombination and diffusion problems in nano-porous membrane.

Electronic structures of IQ4 and IQ22 were calculated and investigated with DFT calculations. The selected Kohn-Sham (KS) molecular orbital distributions and energies of IQ4 and IQ22 are shown in Table S1 and Table S2, respectively. For both IQ4 and IQ22, the KS HOMO is mainly located on the strong electron-donating unit of indoline, while more centralized on indoline group for IQ22. The location of KS LUMO is on the electron-withdrawing unit of cyanoacetic acid, and was not affected by the alkane chains added. In Scheme 1, the energy level schemes of selected Kohn-Sham orbitals of IQ4 and IQ22 are shown, indicating good charge separation after excitation by photons.

Time-dependent DFT (TDDFT) calculations allow comparison of absorption spectroscopy both experimentally and theoretically, and thus the electronic transitions were studied (Figure 2a). The TDDFT calculations for IQ4 and IQ22 show broadly good agreement with experimental
absorption spectra, and the pathways for excitation and electron injection process can be learned by studying the computational results. For IQ22, the first electronic transition, which is calculated to be at 521 nm, is characterized by HOMO → LUMO contribution (52%) and HOMO-1 → LUMO contribution (39%), and the absorption at 413 nm is mainly composed of HOMO → LUMO +1 (47%) and HOMO-1 → LUMO (29%). For IQ4, the calculated low-energy electronic transition (at 483 nm) is composed of HOMO → LUMO (69%) and HOMO -1 → LUMO (21%), and the second electronic transition (at 384 nm) is composed of HOMO -1 → LUMO (51%) and HOMO → LUMO +1 (23%). The lowest energy transition for both dyes is dominated by exciting electrons from HOMO to LUMO orbitals, and the oscillator strength is nearly doubled through structural modification for IQ22.

**Experimental Energy Levels and Orbital Distributions.** The electrochemical characterization combined with UV-Vis spectrum can be used to estimate the molecular energy level position and distribution. As shown in Figure S2 (cyclic voltammetry curves), the first redox potentials (E_{OX}) for IQ22 and IQ4 are 0.82 and 0.61 V (vs NHE) (shown in Table 1), respectively. The introduction of methoxy units into IQ22 shifts E_{OX} 0.21 V negative due to its electronic donor property. Correspondingly, estimated from the optical gap E_{0-0} (from the absorption thresholds of the UV-Vis spectra) and E_{OX}, the excited state reduction potentials (E^{*}_{RED}) of dyes IQ22 and IQ4 are -1.10 and -1.32 V, respectively. Due to an almost unchanged E_{0-0}, dye IQ22 shows a lower E^{*}_{RED} value due to its E_{OX} level lying at lower energy compared with IQ4. The orbital distributions and the E_{OX} and E^{*}_{RED} values are expected to ensure strong directionally efficient electron injection into the conduction band of TiO\textsubscript{2}. This did not influence the current of Qs-DSSCs based on IQ22 thanks to it located in essential energy level scope.\textsuperscript{38} Moreover, the other difference of CV curves for IQ22 and IQ4 is two pairs of submits were
observed for IQ22. In previous investigations, for the sensitizer based on quinoxaline group with alkoxy chains, a single oxidation peak appeared in its CV curve, but for that containing CPDT unit, two obvious oxidation peaks were got. Therefore, two oxidation peaks in CV for IQ22 is owing to CPDT unit was involved in the redox process in addition to the electron donor indoline.

**Solar Cell Performances.** To compare the photovoltaic performance of Qs-DSSCs with the traditional volatile-electrolyte iodine-based devices, we prepared a set of devices sensitizing 8 µm mesoporous TiO$_2$ films with sensitizer IQ22 or IQ4. The current-voltage ($J$-$V$) curves of devices measured under Am 1.5G illumination (100 mW cm$^{-2}$ at 298 K) are shown in Figure 3, with the corresponding photovoltaic parameters listed in Table 1. As a result, using volatile iodine electrolyte, we obtained a solar-to-electric conversion efficiency of 9.83 % ($J_{SC} = 18.36$ mA cm$^{-2}$, $V_{OC} = 748$ mV, $FF = 0.72$) and 9.51% ($J_{SC} = 17.58$ mA cm$^{-2}$, $V_{OC} = 743$ mV, $FF = 0.73$) based on IQ22 and IQ4, respectively. In contrast, the PCEs are 8.76 % ($J_{SC} = 18.19$ mA cm$^{-2}$, $V_{OC} = 715$ mV, $FF = 0.67$) and 8.30 % ($J_{SC} = 17.44$ mA cm$^{-2}$, $V_{OC} = 707$ mV, $FF = 0.67$) based on IQ22 and IQ4, respectively.

**Table 1.** Photophysical and electrochemical properties of sensitizers and photovoltaic parameters of DSSCs based on IQ22 and IQ4 with volatile and gel electrolyte.

<table>
<thead>
<tr>
<th>Dyes</th>
<th>$\lambda_{max}^{d}$ nm</th>
<th>$\varepsilon^{b}$ M$^{-1}$ cm$^{-1}$</th>
<th>$\lambda_{max}^{c}$ nm</th>
<th>$E_{OX}^{d}$ eV</th>
<th>$E_{0-0}^{e}$ eV</th>
<th>$E_{*RED}^{f}$ V</th>
<th>$J_{SC}$ mA cm$^{-2}$</th>
<th>$V_{OC}$ mV</th>
<th>$FF$</th>
<th>$\eta$</th>
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</thead>
<tbody>
<tr>
<td>IQ22-V</td>
<td>555</td>
<td>63200</td>
<td>516</td>
<td>0.82</td>
<td>1.92</td>
<td>-1.10</td>
<td>18.36</td>
<td>748</td>
<td>0.72</td>
<td>9.83</td>
</tr>
<tr>
<td>IQ22-G</td>
<td>516</td>
<td>63200</td>
<td>516</td>
<td>0.82</td>
<td>1.92</td>
<td>-1.10</td>
<td>18.19</td>
<td>715</td>
<td>0.67</td>
<td>8.76</td>
</tr>
<tr>
<td>IQ4-V</td>
<td>531</td>
<td>25700</td>
<td>497</td>
<td>0.61</td>
<td>1.93</td>
<td>-1.32</td>
<td>17.58</td>
<td>743</td>
<td>0.73</td>
<td>9.51</td>
</tr>
<tr>
<td>IQ4-G</td>
<td>531</td>
<td>25700</td>
<td>497</td>
<td>0.61</td>
<td>1.93</td>
<td>-1.32</td>
<td>17.44</td>
<td>707</td>
<td>0.67</td>
<td>8.30</td>
</tr>
</tbody>
</table>

Note: a V: Volatile electrolyte; G: Gel electrolyte. b Absorption parameters were obtained in CH$_2$Cl$_2$. c Absorption parameters were obtained on 4 µm nanocrystalline TiO$_2$ film. d The $E_{OX}$ was obtained in CH$_2$Cl$_2$ with ferrocene (0.63 V vs. NHE) as external reference. e $E_{0-0}$ values were estimated from the wavelength at 10% maximum absorption intensity for the dye-loaded 3 µm nanocrystalline TiO$_2$ film. f The $E_{*RED}$ was calculated according to $E_{*RED} = E_{OX} - E_{0-0}$. (4 µm transparent layer + 4 µm scattering layer) mesoporous TiO$_2$ films with sensitizer IQ22 or IQ4.
$V_{OC} = 707$ mV, FF = 0.68) for IQ22 and IQ4 with gel electrolyte, respectively. Due to poorer charge transport in viscous quasi-solid electrolyte, the electronic recombination probability increases, resulting in the open-circuit voltage reduction for IQ22-G and IQ4-G compared with IQ22-V and IQ4-V, respectively. Of great significant, no matter with volatile or gel electrolyte, we obtained almost the same photocurrent, which is of great importance to the development of stable DSSCs with high power conversion in the future. It also indicates the preferable electron injection and regeneration performance for the IQs sensitizer, especially for IQ22. Notably, $J_{SC}$ estimated from IPCE spectra are broadly comparable with those obtained from the $J-V$ curves, and the integration of IPCE curve for IQ22-V, IQ22-G, IQ4-V and IQ4-G are 17.69, 17.33, 16.85 and 16.69 mA cm$^{-2}$, respectively. The slightly lower values may be interpreted in terms of more efficient charge transport and collection$^{42}$ due to a thermal effect associated with the full sunlight irradiation.$^{43}$

**The Impact of Molecular Structure on Short-Circuit Photocurrent.** With the same assembling condition for devices, the contribution to the enhancement of photocurrent can be attributed to the improvement of the sensitizer’s photoresponse region, absorption intensity and energy levels.
**Figure 3.** The $J$-$V$ curves for DSSCs based on IQ22 (a) and IQ4 (b) with volatile and gel electrolyte.

As shown in Figure 4a, the light harvesting efficiency (LHE) spectra were calculated from the absorption spectra of the dye-loaded TiO$_2$ films (LHE = $1 \times 10^{-\alpha}$, where $\alpha$ is the intensity of the light absorption). For IQ22, the expanded conjugated system with CPDT improves the molar extinction coefficient and broadens the absorption spectrum, so its LHE showed significant enhancement in the visible range of 450-700 nm. To shed light on the contribution of absorption at different wavelengths to the $J_{SC}$, we also measured the incident-photon-to-current conversion efficiency (IPCE) action spectra for the DSSCs based on the IQ22 and IQ4 with volatile or gel electrolyte (Figure 4b). As shown in Figure 4b, almost all the IPCE values between 300-800 nm slightly decrease for the gel electrolyte with IQ22 or IQ4, which is due to its higher viscosity hence lower conductivity. But for IQ22 compared with IQ4, the higher and broader IPCE spectrum with volatile or gel electrolyte can be attributed to its larger conjugated system and branched structure further improving the intramolecular charge separation and charge recombination inhibitory ability which is highly beneficial to the $J_{SC}$ of Qs-DSSC.

**The Determinants of Open-Circuit Voltage.** Electrochemical impedance spectroscopy was used to investigate the origin of the $V_{OC}$ variation for DSSCs sensitized with IQ22 and IQ4. According to reference, there are two main factors that result in the variation of DSSC $V_{OC}$. The first is a conduction band shift and the second is recombination of injected electrons with the oxidized sensitizer or electrolyte.
Figure 4. a) LHE spectra calculated from the absorption spectra of dye-loaded TiO$_2$ film; b) IPCE spectra of DSSCs sensitized by IQ22 and IQ4 with gel or volatile electrolyte.

As a downward shift of the TiO$_2$ conduction band would increase the density of occupied states (DOS) which are directly proportional to chemical capacitance ($C_{\text{chem}}$), measurement of $C_{\text{chem}}$ as a function of potential bias allows insight into the DOS in devices made with different dyes. As presented in Figure 5a and b, $C_{\text{chem}}$ is lower for IQ22 with both electrolytes at a given voltage indicating an upward shift of the conduction band due to the increase of dipole. It indicates the upward shift of the conduction band as one of the origins for the increase $V_{\text{OC}}$ in IQ22-sensitized DSSCs (as listed in Table 1).

To obtain insight into the electron recombination occurring between excited electrons in the conduction band and sensitizers or electrolyte, the electron lifetimes were explored as a function of potential bias (Figure 5c and d). At a given potential, the electron lifetime in cell sensitized with IQ22 was obviously longer than that with IQ4 based on gel (Figure 5c) or volatile electrolyte (Figure 5d). It further demonstrates that the branched alkyl chains for IQ22 effectively suppress the electron recombination on the TiO$_2$ surface improving the electron lifetime. Especially, the major difference in lifetime for gel electrolytes (Figure 5c) with the serious charge recombination
reflects the superior suppressing effect of the branched structure in IQ22. Therefore, the longer electron lifetime is another origins for the higher $V_{OC}$ of IQ22.

**Figure 5.** Chemical capacitance and electron lifetime as a function of bias potential obtained through electrochemical impedance spectroscopy carried out on devices with gel electrolyte (a, c) and volatile electrolyte (b, d), respectively in the dark.

**The Stability of Photovoltaic Performance.** To develop Qs-DSSCs, we mainly aimed at the improvement of their thermal and light-exposure stability. As presented in Figure 6, the photovoltaic performance of Qs-DSSCs exhibited excellent stability during a 1000 h accelerated aging for IQ22 and IQ4-based cells with gel electrolyte in a solar simulator under full intensity (100 mW cm$^{-2}$) at 50 °C. In the long term light and thermal environment, the enhancement of $J_{SC}$ from 0 to 100h especially for IQ4 indicated the system changes gradually stabilized due to the improvement of the interfacial contact between TiO$_2$ and electrolyte. The $J_{SC}$ increased significantly at this stage, resulting in an increase in efficiency, although $V_{OC}$ and $FF$ changed slightly to lower values. Along with the increase in $J_{SC}$, $V_{OC}$ decreased because more electron recombination can occur with passage of time. In the light-soaking from 100 to 1000 h, however,
all four photovoltaic parameters remained almost constant, which shows not only the good stability of quasi-solid electrolyte, but also the excellent anti-decomposition property exposure to light and heat for IQs dyes.

**Figure 6.** Stability test of photovoltaic parameters ($V_{OC}$, PCE, $FF$ and $J_{SC}$) variation with aging time for the devices based on IQ22 (blue line) and IQ4 (red line) with quasi-solid-state electrolyte during 1 sun visible-light soaking at 50 °C.

**CONCLUSIONS**

In summary, we have demonstrated IQ22 as an effective sensitizer for Qs-DSSC devices, with a high power conversion efficiency. For the optimum Qs-DSSC based on IQ22, a metal-free organic sensitizer, the PCE reached 8.76% with high $J_{SC}$ (18.19 mA cm$^{-2}$). Due to the lower conductivity and higher charge recombination for the gel electrolyte, the superior performance can be attributed to the structural design with high conjugation unit (broadening the photoresponse spectrum) and branched alkyl chains (boosting the electronic recombination suppression). As a consequence, no matter which electrolyte we choose, the determining factors for the higher open-circuit voltage of IQ22 compared with IQ4 are its positive shift of conduction band and longer electronic lifetime. Overall, we obtain efficient and stable DSSCs, using low-cost organic sensitizers for Qs-DSSCs with excellent energy matching properties, advancing the practical application of DSSCs.
EXPERIMENTAL SECTION

Cell Assembly: The working electrode was composed of an 8 µm thick TiO₂ film, including a 4 µm transparent layer with 18 NRT and 4 µm scattering layer with 18NR-AO. The dye solutions were 0.3 mM in chloroform/ethanol (3/7) and the photoanodes underwent dipping for 12 h to complete the loading with sensitizers. The dye-covered TiO₂ electrode and Pt-counter electrode were assembled into a sandwich type cell and sealed with a hot-melt gasket of 45 µm thickness made of the ionomer Surlyn 1702 (DuPont) with a heat sealing machine. The size of TiO₂ electrodes used was 0.25 cm² (i.e., 5 mm×5 mm). For the liquid state device, a drop of the electrolyte was put on the hole in the back of the counter electrode. It was introduced into the cell via vacuum backfilling. The hole in the counter electrode was sealed by an aluminum foil tape. For the Qs-DSSCs, the electrolyte was spreaded on the TiO₂ film before packaging with Surlyn ring and Pt electrode and then hot-pressed. Both conductivity and Tafel polarization curves were recorded by assembling symmetric dummy cells consisting of Pt CE|electrolyte|Pt CE. The volatile iodine electrolyte contained: 0.5 M BMII (1-butyl-3-methylimidazolium iodide), 0.1 M DMPII (1, 2-dimethyl-3-propylimidazolium iodide), 0.05 M I₂, 0.1 M LiI, 0.1 M GuSCN (guanidinium thiocyanate) and 0.5 M 4-tert-butylpyridine in a mixture of acetonitrile and valeronitrile (volume ratio, 85 : 15). The polymer gel electrolyte (OPV-MPV-I) was a product of Yingkou OPV Tech New Energy Co, Ltd. (Liaoning, China), and it contains polymer, LiI, 3-methoxypropionitrile (MPN), I₂, guanidine thiocyanate (GuSCN) and 4-tert-butylpyridine (TBP). 9-10

SYNTHESIS AND CHARACTERIZATION OF COMPOUNDS:

Synthesis of IQ22a. The unpurified indoline borate THF solution was reacted with 5,8-dibromo-2,3-(4-methoxyphenyl) quinoxaline (1.0 g, 2.72 mmol) under Suzuki coupling reaction using Pd(PPh₃)₄ (40 mg) and K₂CO₃ aqueous solution (30 mL, 2 M) as catalysts in 80 mL THF for 12
h. After cooling, water was added and the reaction mixture was extracted with CH$_2$Cl$_2$. The combined organic layer was washed with H$_2$O and brine, dried over anhydrous Na$_2$SO$_4$, and evaporated under reduced pressure. The crude product was purified by column chromatography (CH$_2$Cl$_2$/PE = 1/3) on silica gel and the product was obtained as a red solid, 22a (270 mg, 0.61 mmol, 72%). $^1$H NMR (400 MHz, DMSO-d$_6$, δ): 7.88 (d, J = 8 Hz, 1H), 7.82 (d, J = 8 Hz, 1H), 7.56-7.70 (m, 5H), 7.13 (d, J = 4.8 Hz, 1H), 6.84-6.92 (m, 3H), 6.82 (d, J = 8.0 Hz, 2H), 3.79 (s, 3H), 3.77 (s, 3H), 1.75-1.89 (m, 4H), 1.02-1.15 (m, 20H), 0.88-1.00 (m, 4H), 0.74 (t, J=5.8 Hz, 6H). $^{13}$C NMR (100 MHz, DMSO-d$_6$, δ): 159.62, 159.49, 157.50, 156.63, 151.52, 150.68, 140.12, 137.52, 136.98, 136.37, 135.91, 132.24, 131.54, 130.88, 130.63, 130.04, 129.88, 124.83, 124.32, 120.64, 120.32, 120.00, 112.79, 54.29, 52.42, 36.88, 30.78, 29.10, 28.34, 28.27, 23.61, 21.59, 13.05.

**Synthesis of IQ22b.** 5 mL of dry dimethylformamide (DMF) was dissolved in 10 mL CH$_2$Cl$_2$ and cooled in an ice bath to 0°C. In a separate vessel, 3 mL of phosphorus oxychloride was dissolved in 5 mL CH$_2$Cl$_2$, and this solution was added to the solution of DMF dropwise with continuous stirring at 0 °C for 1 hour. After the addition was complete, 22a dissolved in 20 mL of CH$_2$Cl$_2$ was added, dropwise with stirring. The solution was brought to room temperature overnight. The mixture was washed with water and extracted with CH$_2$Cl$_2$ until the color was removed. The combined organic extract was dried over sodium sulfate, Na$_2$SO$_4$, and evaporated to remove solvent under reduced pressure. The origin oil obtained was purified by column chromatography (CH$_2$Cl$_2$/PE = 2/3) and the product was obtained as an orange solid, 22b (220mg , 68%). $^1$H NMR (400 MHz, CDCl$_3$, δ): 9.84 (s, 1H, -COH), 7.99 (d, J=8.1 Hz, 1H, Ph-H), 7.91 (m, J=8.1 Hz, 1H, Ph-H), 7.74 (s, 1H, thienyl-H), 7.66~7.72 (m, 4H, Ph-H), 7.65 (s, 1H, thienyl-H), 6.87~6.98 (m, 4H, Ph-H), 3.89 (s, 3H, -O-CH$_3$), 3.86 (s, 3H, -O-CH$_3$), 1.56 (s, 6H, -C-CH$_3$).
**Synthesis of 22c.** The indoline borate THF solution was prepared from 7-bromo-1,2,3,3a,4,8b-hexahydro-4-(4-methylphenyl)-cyclopent[b]indole (160 g, 0.50 mmol). The unpurified indoline borate THF solution was reacted with 22b (200 mg, 0.25 mmol) under Suzuki coupling reaction using Pd(PPh$_3$)$_4$ (10 mg, 8 mmol) and K$_2$CO$_3$ aqueous solution (4 mL, 2 m) as catalysts in 15 mL THF for 12 h. After cooling, water was added and the reaction mixture was extracted with CH$_2$Cl$_2$. The combined organic layer was washed with H$_2$O and brine, dried over anhydrous Na$_2$SO$_4$, and evaporated under reduced pressure. The crude product was purified by column chromatography (CH$_2$Cl$_2$/PE = 1/2) on silica gel and the product as obtained as a deep red solid, 21c (150 mg, 0.16 mmol, 64%). 1H NMR (400 MHz, CDCl$_3$, δ): 9.93 (s, 1H), 8.21 (d, J=8 Hz ,1H), 7.85-7.87 (m, 4H), 7.82 (s, 1H), 7.73 (d, J=8.8 Hz, 2H), 7.67 (s, 1H), 7.61-7.63 (m, 1H), 7.31 (d, J=8.4 Hz, 2H), 7.24 (d, J=8 Hz,2H), 7.13 (d, J=8.4 Hz, 1H), 7.05 (d, J=8.8 Hz, 2H), 6.91 (d, J=8.8 Hz, 2H), 4.88-4.95 (m, 1H), 3.96-3.98 (m, 4H), 3.87 (s, 3H), 2.47-2.58 (m, 3H), 2.10-2.25 (m, 2H), 1.98-2.08 (m, 5H), 1.86-1.95 (m, 1H), 1.72-1.82 (m, 2H), 1.20-1.32 (m, 20H), 1.10-1.19 (m, 4H), 0.89-1.38 (m, 6H). 13C NMR (100MHz, CDCl$_3$, δ): 182.45, 161.94, 160.54, 160.34, 157.95, 150.88, 150.68, 148.78, 147.84, 144.74, 143.10, 140.43, 139.40, 138.90, 138.48, 136.97, 134.54, 131.90, 131.72, 131.61, 131.42, 131.29, 130.19, 130.08, 129.84, 128.37, 128.02, 127.81, 126.65, 120.02, 113.91, 107.26, 69.22, 55.38, 55.31, 53.91, 45.62, 37.94, 35.16, 33.88, 31.89, 30.16, 29.45, 29.37, 24.80, 24.65, 22.71, 20.89, 14.19.

**Synthesis of IQ22.** A mixture of aldehyde 22c (150 mg, 0.16mmol) and cyanoacetic acid (17 mg, 0.20 mmol) in acetonitrile (16mL) was refluxed in the presence of piperidine (0.5 mL) for 7 h under argon. After it cooled, the mixture was diluted with CH$_2$Cl$_2$, washed with water and brine, dried over Na$_2$SO$_4$, and evaporated under reduced pressure. The crude product was purified by column chromatography with 1% acetic acid in CH$_2$Cl$_2$ on silica gel to yield the product as a purple
powder. 1H NMR (400 MHz, THF-d₈, δ): 8.18(d, J=8 Hz, 1H), 7.87(s, 1H), 7.72(d, J=8 Hz, 1H), 7.68(d, J=4 Hz, 2H), 7.66(d, J=4 Hz, 2H), 7.53(d, J=12 Hz, 2H), 7.43(d, J=12 Hz, 1H), 7.16(d, J=8 Hz, 2H), 7.05(d, J=8 Hz, 2H), 6.90(d, J=8 Hz, 3H), 6.76(d, J=8 Hz, 2H), 4.80(t, J=8 Hz, 1H), 3.83(t, J=8 Hz, 1H), 3.75(s, 1H), 3.68(s, 3H), 2.21(s, 3H), 1.90-1.96(m, 6H), 1.0-1.15(m, 20H), 0.95-0.99(m, 4H), 0.71(t, J=5.8 Hz, 6H). 13C NMR (400 MHz, THF-d₈, δ): 160.28, 140.07, 136.22, 131.17, 130.86, 130.52, 129.29, 129.10, 128.25, 128.19, 127.94, 127.15, 125.86, 119.26, 112.86, 54.36, 54.26, 53.19, 45.04, 38.13, 33.18, 31.42, 31.32, 29.61, 29.14, 28.88, 25.11, 24.39, 23.76, 22.04, 13.05. HRMS (ESI, m/z, [M + H]⁺). Calcd for C₆₉H₇₂N₄O₄S₂: 1085.5073. Found: 1085.5081.

**Computational methods.** The molecular structures of IQ4 and IQ22 were firstly optimised under vacuum condition, with the starting geometries entered from software Avogadro. 49 Then from the optimised geometry from vacuum, further optimization was carried out with the presence of dichloromethane polarizable continuum model (PCM). All the calculations were performed using Gaussian 09 (R. A. Gaussian 09, M. J. Frisch, G. W. Trucks, H. B. Schlegel et al. Gaussian, Inc., Wallingford CT, 2009.) with hybrid B3LYP functional level of theory and standard 6-31G (d) basis set. Time-dependent DFT calculations (TD-DFT) 50-51 were carried out using Gaussian 09 program with PCM in Dichloromethane. CAM-B3LYP functional 52 was used, and total of 70 lowest singlet electronic transitions were calculated and further processed with GaussSum software package. 53

**ASSOCIATED CONTENT**
**Supporting Information.** Electronic Supplementary Information (ESI) available: See DOI: 10.1039/x0xx00000x including *Materials and Characterization, Synthesis and characterization of compounds* and *Density Functional Theory (DFT) Calculation.*

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**Author Contributions**

Yu Wang and Zhiwei Zheng contributed equally to this work.

**Notes**

The authors declare no competing financial interest.

**ACKNOWLEDGEMENTS**

This work was supported by NSFC for Creative Research Groups (21421004), the Programme of Introducing Talents of Discipline to Universities(B16017) and Distinguished Young Scholars (21325625), NSFC/China, Oriental Scholarship, Fundamental Research Funds for the Central Universities (WJ1416005 and WJ1315025), and the Scientific Committee of Shanghai (14ZR1409700 and 15XD1501400) for financial support.

**REFERENCE**


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A novel D-A-π-A configuration organic sensitizer IQ22 was specifically designed with broad light response and high molar extinction coefficient for increasing the short-circuit current density ($J_{sc}$), and improving the open-circuit voltage ($V_{oc}$). And a promising conversion efficiency as high as 8.76% was got, standing out in the Qs-DSSCs utilizing metal-free organic sensitizers.