A Novel Organic Redox Electrolyte Rivals Triiodide/iodide in Dye-Sensitized Solar Cells

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1. Experimental section

Synthesis of the redox molecules:
5-mercapto-1-methyltetrazole N-tetramethylammonium salt (NMe₄⁺T⁻) was prepared by neutralization of 5-mercapto-1-methyltetrazole (1.46 g, 12.6 mmol) (Aldrich, 98%) with a 25 wt.% solution of tetramethylammonium hydroxide in methanol (1.4 mL, 13.3 mmol) (Aldrich) added dropwise. The reaction was performed in a glove box under argon atmosphere. The mixture was stirred at room temperature for 12 h to allow complete reaction. The solvent was evaporated and the resulting white solid was dried under vacuum at 40°C for 48 h with P₂O₅ (EMD, ACS). No impurity was detected by ¹H NMR (300 MHz, Varian).

C₆H₁₅N₅S
189.28 g/mol
Melting point = 171-173°C
¹H NMR (300 MHz, DMSO-d₆, ppm): δ = 3.61 (s, 3H, CH₃), 3.10 (s, 12H, NMe₄⁺).
MS data were acquired using Agilent LC/MSD TOF model 6210 with electrospray ionization (ESI) in positive mode. It was not possible to observe the molecular mass of 5-mercapto-1-methyltetrazole N-tetramethylammonium salt* (\(\text{^\text{+}}\text{NMe}_4\text{ T}^{-}\)) from direct injection by TOF ESI MS analysis. However, positive detection mode gave the mass for the corresponding T\(^{-}\) anion: TOF ESI (+) EIC mode MS exact mass: calc’d for C\(_2\)H\(_4\)N\(_4\)S = 116.0157 (M\(^{-}\) + H\(^{+}\)); found = 116.0155 (\(\Delta =1.83\) ppm). The same sample gave the mass for the corresponding \(\text{^\text{+}}\text{NMe}_4\) cation: mass: calc’d for C\(_4\)H\(_{12}\)N = 74.0964 (M\(^{+}\)); found = 74.0971 (\(\Delta = 9.1\) ppm).

[*NB. It was possible to observe the corresponding potassium salt (K\(^{+}\) T\(^{-}\)): TOF ESI (+) EIC mode MS exact mass: calc’d for C\(_2\)H\(_3\)N\(_4\)SK = 153.9715; found = 153.9718 (\(\Delta = 1.83\) ppm)].

di-5-(1-methyltetrazole) disulfide (T\(_2\)) was prepared from oxidation of 5-mercapto-1-methyltetrazole (4.0 g, 34.4 mmol) by iodine (4.0 g, 15.8 mmol) (Aldrich, 99.8%) in water. The mixture was sonicated for 1 h until I\(_2\) disappeared. The white precipitate was then collected by filtration under vacuum, washed thoroughly with cold nanopure water (4°C) and dried under vacuum at 40 °C for 48 h.

C\(_4\)H\(_6\)N\(_8\)S\(_2\)
230.28 g/mol
Melting point = 112°C (literature: 112°C)

\(^1\)H NMR (300 MHz, DMSO-\(d_6\), ppm): \(\delta = 4.04\) (s, 6H, CH\(_3\)).

TOF ESI (+) EIC mode MS exact mass: calc’d for C\(_4\)H\(_7\)N\(_8\)S\(_2\) = 231.0230 (M + H\(^{+}\)); found = 231.0234 (\(\Delta = 1.77\) ppm).

Electrochemical characterization of the redox couple: Cyclic voltammetry (CV) experiments (in Figure S1) were performed at 22 °C in a one-compartment glass cell using a three-electrode configuration. A 0.0707 cm\(^2\) glassy carbon (GC) electrode (BAS) served as the working electrode, Ag wire (Acros Organics, 99.9%, d=0.5 mm) was the (pseudo) reference electrode (0.144 V vs NHE as measured by CV using 25 mM ferrocene in the same medium) and a 1 cm\(^2\) Pt foil (Aldrich, 99.9%, 0.1 mm thick) was used as the counter electrode. Before use, the GC disk was polished to a mirror finish on a polishing cloth (Buhler) with a 1 \(\mu\)m diamond paste and then a 0.05 \(\mu\)m
alumina slurry, and washed with nanopure water. The electrode was then cleaned by sonication (10 min for each solvent) successively in ethanol, nanopure water and acetone. The electrolyte solution was prepared by dissolving 100 mM NMe₄⁺T⁻ and 10 mM T₂ in the solvent mixture anhydrous N, N-dimethylformamide (DMF, Alfa Aesar, ACS 99.8%)/anhydrous dimethylsulfoxide (DMSO, Aldrich, 99.9+%) (60/40 v/v) containing 0.2 M tetra-N-butylammonium perchlorate (TBAP, Alfa Aesar, electrochemical grade, recrystallized in ethyl acetate) as the supporting electrolyte. A multipotentiostat (Solartron Instruments, model 1480) was interfaced with a PC and the electrochemical parameters were controlled with the CorrWare software (Scribner Associates, version 2.80c). CV experiments were carried out at 22 °C over the potential range -0.6 to 1.2 V vs Ag at a scan rate of 50 mV s⁻¹.

Device fabrication: Screen-printed double layer of TiO₂ particles were used as photoelectrodes in this study. An 8 or 11 μm thick film of 20 nm-sized TiO₂ particles was first printed on the fluorine doped SnO₂ (FTO) conducting glass electrode and further coated with a 5 μm thick second layer of 400 nm light-scattering anatase particles (CCI, Japan) with the porosity being 67% for the 20 nm TiO₂ transparent layer and 42% for the 400 nm TiO₂ scattering layer, as determined from BET measurements. Detailed methods of TiO₂ film preparation, device fabrication, and photocurrent-voltage measurements were reported in our earlier publications. [1] In brief, the sintered TiO₂ electrodes were stained by adding 30 μl Z907Na dye solution (6 mM in 2-methoxypropanol) on top of the TiO₂ electrode for 5 min, and then assembled with a thermally platinized FTO/glass counter electrode. The working and counter electrodes were separated by a 25 μm thick hot melt ring (Surlyn, DuPont) and sealed by heating. The cell internal space was filled with electrolytes using a vacuum pump. The electrolyte-injecting hole on the thermally platinized FTO glass counter electrode was finally sealed with a Surlyn sheet and a thin glass cover by heating.

Photovoltaic characterization: A 450 W xenon light source (Oriel, USA) was used to characterize the solar cells. The spectral output of the lamp was matched in the region of 350–750 nm with the aid of a Schott K113 Tempax sunlight filter
(Präzisions Glas & Optik GmbH, Germany) so as to reduce the mismatch between the simulated and true solar spectra to less than 2%. The current–voltage characteristics of the cell under these conditions were obtained by applying external potential bias to the cell and measuring the generated photocurrent with a Keithley model 2400 digital source meter (Keithley, USA). A similar data acquisition system was used to control the incident photon-to-collected electron conversion efficiency measurement. Under computer control, light from a 300W xenon lamp (ILC Technology, U.S.A.) was focused through a Gemini-180 double monochromator (Jobin Yvon Ltd., U.K.) onto the photovoltaic cell under test. The monochromator was incremented through the visible spectrum to generate the IPCE ($\lambda$). The devices were masked to attain an illuminated active area of 0.158 cm$^2$. The photovoltaic parameters are average values with statistical error less than 2% based on 3 devices for each tested electrolyte.

**Determination of Electron Recombination Lifetime, Electron Diffusion Coefficients and Density of Electrons in the titania film by Transient Photovoltage Decay and Charge Extraction Measurements:** For the transient photovoltage decay measurements, a white light bias was generated from an array of diodes. Red light pulse diodes (with a square pulse width, 100 ns rise and fall time) controlled by a fast solid-state switch were used as the perturbation source. The voltage dynamics were recorded on a PC-interfaced Keithley 2400 source meter with a 500 $\mu$s response time. The perturbation light source was set to a suitably low level in order for the voltage decay kinetics to be mono-exponential. By varying the white light bias intensity, the electron recombination lifetime could be estimated over a range of applied biases. Before the LEDs switched to the next light intensity, a charge extraction routine was executed to measure the electron density in the film. In the charge extraction techniques, the LED illumination source was turned off in <1 $\mu$s, while simultaneously, the cell was switched from open to short circuit. The resulting current, as the cell returns to $V=0$ and $J=0$, was integrated to give a direct measurement of the excess charge in the film at that $V_{oc}$.

**Electrochemical impedance spectroscopy (EIS)** measurements were carried out with an Autolab Frequency Analyzer set-up which consists of an Autolab PGSTAT 30 (Eco
Chemie B.V., Utrecht, The Netherlands) producing a small amplitude harmonic voltage, and a Frequency Response Analyzer module. For the impedance study on the counter electrode/electrolyte interface in the symmetrical dummy cells, a circuit of the form illustrated in the inset of Figure S5 was used to fit the high frequency end of the spectra with the ‘Z-View’ non-linear least-squares fitting program. The charge transfer resistance \( (R_{ct}) \) presented here was calculated as half the value obtained from the fitting (the cells used were symmetrical) and then multiplied by the geometric area of the electrode. The measurements of \( R_{ct} \) and of the oxidized species diffusion coefficients were performed at 0 V and – 0.6 V (bias applied across the dummy cell) under different temperatures (from -15 to 40 °C) for the chosen electrolyte of the dye-sensitized solar cell. These symmetrical cells were built by sealing two identically prepared electrodes by a 25 µm thick spacer (Surlyn), the space being filled with the electrolyte. Impedance studies on the complete dye-sensitized solar cells were performed at a constant temperature of 20 °C under dark conditions. The impedance spectra of the DSC devices were obtained at various potentials (from -0.8 V to -0.3 V) with analysis frequencies ranging from 0.02 Hz to ~200 kHz, the oscillation potential amplitudes having values of approximately 10 mV. For the dummy cells, the frequency range studied and the oscillation potential amplitudes were identical. In these EIS experiments, the photoanode (the dye-sensitized TiO₂ electrode) was used as the working electrode, the thermal platinized FTO glass counter electrode (CE) being used simultaneously as both the auxiliary electrode and the reference electrode. The spectra obtained were fitted (error<5%) using a transmission line model, which has been described previously. [1,2,3]

The Nanosecond laser flash photolysis technique was applied to dye-sensitized, 8 µm-thick, transparent TiO₂ mesoporous films deposited on normal flint glass. Pulsed excitation (\( \lambda = 532 \) nm, 7 ns pulse duration, 30 Hz repetition rate) was carried out by a Powerlite 7030 frequency-doubled Q–switched Nd:YAG laser (Continuum, Santa Clara, California, USA). The laser beam output was expanded by a planoconcave lens to irradiate a large cross-section of the sample, whose surface was kept at a 30° angle to the excitation beam. The laser fluence on the sample was kept at a low level (40 µJ
cm\(^{-2}\) per pulse) to ensure that, on average, less than one electron is injected per nanocrystalline TiO\(_2\) particle on pulsed irradiation. The probe light, produced by a continuous wave xenon arc lamp, was passed first through a monochromator tuned at 650 nm, various optical elements, the sample, and then through a second monochromator, before being detected by a fast photomultiplier tube. Data waves were recorded on a DSA 602A digital signal analyser (Tektronix, Beaverton, Oregon, USA). Satisfactory signal-to-noise ratios were typically obtained by averaging over 1,500 laser shots.

2. Results and Discussion

Figure S1 shows the cyclic voltammogram of a DMF/DMSO solution containing the NMe\(_4^+\)T\(^-\) (100 mM)/T\(_2\) (10 mM) redox couple and 0.2 M TBAP obtained at a GC electrode at 50 mV s\(^{-1}\). High current densities are observed for this redox couple prepared at a relatively low concentration in the non-aqueous solvent mixture. The solution is quasi-transparent and has a conductivity of 7.56 mS cm\(^{-1}\) at 22\(^\circ\)C, as measured using a small conductivity cell (volume < 1 mL) and electrochemical impedance spectroscopy. The anodic and cathodic peak potentials are 0.763 V and -0.081 V vs Ag, respectively, with an apparent standard potential (E\(_o^\prime\)) of 0.341 V vs Ag or 0.485 V vs NHE.

**Figure S1** Cyclic voltammetry measurements. Cyclic voltammogram of 100 mM NMe\(_4^+\)T\(^-\)/10 mM T\(_2\) redox couple in DMF/DMSO: 60/40 (v/v) with 0.2 M TBAP measured at a 0.0707 cm\(^2\) sized glassy carbon disk electrode. Scan rate = 50 mV s\(^{-1}\).
T− and T2 are colorless whereas their mixture is pale yellow (which absorbs to a negligible extent under thin layer conditions, Figure S2). A \( T_3^- \) (or \( T^-T_2 \)) charge transfer complex could exist in this case. \(^{[4,5]}\) The UV–Vis reflection spectra of electrolytes II (red), IV (green) and V (grey) are shown in Figure S2. These results show that the \( T_2/T^- \) redox couple has practically no light absorption in the visible region.

**Figure S2 Absorption spectra of different electrolytes.** The samples in this experiment (II red line, IV green line, and V grey line) were diluted with acetonitrile/ethylene carbonate (6:4 volume ratio) by a factor of 8. The path length is 2 mm. The original electrolyte composition is as follows: Electrolyte II, 0.4 M T2 and 0.4 M T−; Electrolyte IV, 0.4 M T2 and 0.4 M T− with 0.5 M t-butyl pyridine and 0.05 M LiClO4; and Electrolyte V, 0.8 M DMII and 0.4 M I2. All electrolytes were made with acetonitrile/ethylene carbonate (6:4 volume ratio) as solvent.

**Figure S3 Linear voltammetry measurements.** Direct electrochemical measurement of the dark current as a function of the forward bias for two devices under dark conditions with a scan rate of 50
mV s\(^{-1}\). The electrolyte composition is as follows: Electrolyte II, 0.4 M T\(_2\) and 0.4 M T\(^+\) for device B, and Electrolyte V, 0.8 M DMII and 0.4 M I\(_2\) for device F. All electrolytes were made with acetonitrile/ethylene carbonate (6:4 volume ratio) as solvent.

Figure S3 shows that the T\(_2\)/T\(^+\) redox couple (red, device B) produces a substantially lower dark current compared to that of the I\(_3^-/I^-\) (grey, device F) under forward bias.

Figure S4 shows the response of the short-circuit photocurrent to on–off irradiation at different intensities for a T\(_2\)/T\(^+\) electrolyte (IV) based device (E), whose TiO\(_2\) film thickness was 11±5 μm. The initial value for the photocurrent normalized to 100 mW cm\(^{-2}\) was constant at 15.9 ± 0.2 mA cm\(^{-2}\), indicating that the signal measured immediately after opening the shutter scaled linearly with the light intensity inferring that the fill factor is not limited by diffusion of T\(_2\). During the 3.5 s light exposure, the photocurrent was stable showing a linear response to the light intensity.

![Figure S4 Photocurrent dynamics. Characteristics of current dynamics of a Z907Na-sensitized solar cell (device E). Photocurrent dynamics obtained using electrolyte IV and a 11±5 μm thick double layer nanocrystalline TiO\(_2\) electrode. Solid lines represent the measured photocurrents and dotted lines represent the photocurrents scaled to 1 sun by multiplying by the attenuation factor.](image)

Using EIS, the electrochemical activity of the different electrolytes on Pt/FTO counter electrodes was characterized. Figure S5 shows the Nyquist plot obtained at 20 °C from dummy cells prepared by using Pt as the electrocatalyst. The charge transfer resistance (R\(_{ct}\)) was measured by fitting the arc observed at higher frequencies.
(leftmost semicircle) to the Randles circuit shown in the inset of Figure S5, consisting of $R_{ct}$ in series with the Warburg impedance ($W_s$), both of which are in parallel with a double layer capacitance ($C_{dl}$). A series resistance ($R_s$) was introduced to describe the ohmic resistance of the load and the conducting substrate. $W_s$ arises from mass transport limitations due to diffusion in the electrolytes and its characteristic diffusion time constant ($\tau_d$) can be used to calculate the electroactive species diffusion coefficients, namely of T$_2$ when the dummy cell is biased at -0.6 V:

$$D = \left( \frac{d^2}{\tau_d} \right)$$  

(S1)

where $d$ is the diffusion length (taking half of the gap value between the two electrodes in this experiment).

**Figure S5 Electrochemical impedance spectroscopy.** Typical Nyquist plot from impedance measurements on the thin layer cells: CE//electrolyte//CE. The Randles circuit is shown in the inset, including a component $R_s$=series resistance, $R_{ct}$=charge transfer resistance, $C_{dl}$=double layer capacitance, and $W_s$=Warburg impedance. The solid lines are the fitted curves. The electrolyte used in this figure is Electrolyte IV.
Figure S6 Temperature-dependent apparent T\textsubscript{2} diffusion coefficients of different electrolytes. The electrolyte composition is as follows: Electrolyte I, 0.1 M T\textsubscript{2} and 0.4 M T\textsuperscript{−}; Electrolyte II, 0.4 M T\textsubscript{2} and 0.4 M T\textsuperscript{−}; Electrolyte III, 1.0 M T\textsubscript{2} and 0.4 M T\textsuperscript{−}; Electrolyte IV, 0.4 M T\textsubscript{2} and 0.4 M T\textsuperscript{−} with 0.5 M t-butyl pyridine and 0.05 M LiClO\textsubscript{4}, and Electrolyte V, 0.8 M DMII and 0.4 M I\textsubscript{2}. All electrolytes were made with acetonitrile/ethylene carbonate (6:4 volume ratio) as solvent.

As shown in Figure S6, the T\textsubscript{2}/T\textsuperscript{−} redox couple based electrolytes show an apparent T\textsubscript{2} diffusion coefficient of 1.3~2.1×10\textsuperscript{−5} cm\textsuperscript{2} s\textsuperscript{−1} at 20 °C. According to the data in Figure S6, the diffusion coefficient decreased with increasing the concentration of the T\textsubscript{2} salt, which could be due to enhanced viscosity of the electrolyte. The addition of TBP and LiClO\textsubscript{4} increases slightly the diffusion coefficients (see electrolytes II, red, and IV, blue). These values are close to the I\textsuperscript{3}/I\textsuperscript{−} system, indicating there is no ionic diffusion problem in the devices using T\textsubscript{2}/T\textsuperscript{−} in this study.

The exchange current density, \(J_0\), is an important kinetic parameter representing the electrochemical reaction rate at equilibrium, i.e., the equal cathodic and anodic currents normalized to the projected electrode area at equilibrium, and is calculated from \(R_{ct}\) (Figure S7a) using the following equation:

\[
J_0 = \frac{RT}{nF R_{ct}} 
\]  

(\textit{S2})

where \(R_{ct}\) is a charge transfer resistance, determined by impedance spectra data, and \(R\), \(T\), \(n\) and \(F\) have their usual significance.
$J_0$ shows temperature dependence (Figure S7b), following the Arrhenius equation:

$$J_0 = I_0 e^{-\left(\frac{E_\alpha}{RT}\right)}$$  \hspace{1cm} (S3)

where $I_0$ is the exchange current density at $T = \infty$ and $E_\alpha$ is the activation energy. As shown in Figure S7b, the $T_2/T^-$ redox couple has a relatively low $J_0$ value on the Pt electrode, which is contributing to the lower fill factor of this cell.

**Figure S7 Equivalent circuit components derived from impedance measurements.** Charge transfer resistance ($R_{ct}$) -temperature ($T$) (a) and exchange current density ($J_0$) -temperature data (b) in the Arrhenius coordinates obtained by impedance measurements of thin layer symmetrical (CE/electrolyte/CE) cells. The electrolyte composition is as follows: Electrolyte I, 0.1 M $T_2$ and 0.4 M $T^-$; Electrolyte II, 0.4 M $T_2$ and 0.4 M $T^-$; Electrolyte III, 1.0 M $T_2$ and 0.4 M $T^-$; Electrolyte IV, 0.4 M $T_2$ and 0.4 M $T^-$ with 0.5 M t-butyl pyridine and 0.05 M LiClO$_4$, and Electrolyte V, 0.8 M DMII and 0.4 M I$_2$. All electrolytes were made with acetonitrile/ethylene carbonate (6:4 volume ratio) as solvent.

In the transient photovoltage decay experiments, different steady-state lights were supplied using a home-made white light-emitting diode array by tuning the driving voltage, and a red light-emitting diode array controlled by a fast solid-state switch was used to generate a perturbation pulse. Figure S8 shows the transient photovoltage curves of device B with $T_2/T^-$ and of device F with $I_2^+/I^-_2$ at open circuit under a white LED light illumination (23.8 mW cm$^{-2}$), serving as an illustrative example of the technique. The information on the characteristic lifetime ($\tau_2$) for interfacial charge
recombination \( T_{2-e_TiO_2} \) can be obtained from the temporal decay of the photovoltage following the probe pulse. In the text, the electron recombination lifetime was compared under the same electron population in the TiO_2 substrate (see Figure 4b). The photovoltage rise time, \( \tau_{\text{rise}} \), provides information on the electron transport rate \( (\tau_{\text{trans}}) \) within the nanocrystalline titania particle network. \[^6,7\] Recombination of electrons injected into the semiconductor with the oxidized species at the interface \( \left( 2e^-_{TiO_2} + T_2 \rightarrow 2T^+ \right) \), assuming that a first electron-transfer is the rate limiting step and the overall process is first order in electron concentration \( (n_t) \), corresponding to dark current \( (j_{\text{dark}} \sim kn_t[r'_2] \sim n_t/\tau_0 , k \) being the rate constant, \( \tau_0 \) being the electron lifetime), is one of the primary loss processes in a DSC, which contributes to the diminishment of device PV performance.

**Figure S8 Photovoltage decay measurements.** Transient photovoltage rise and decay measurement for a red pulse light incident on the FTO side of a DSC based on thin TiO_2 nanocrystalline film with different electrolytes (II for device B and V for device F). Red light pulse diodes controlled by a fast solid-state switch were used as the perturbation sources. The photovoltage rise time and decay time were estimated by using the convolve operation within Igor Pro 6.02A software (WaveMetrics, Inc.).

Figure S9 illustrates the chemical capacitance \( (C_{\text{ch}}) \) of the TiO_2 film obtained from transient photovoltage and photocurrent decay impedance measurements. The chemical capacitance is defined as the amount of electronic charge necessary for increasing the Fermi level of the nanocrystalline oxide film by 1 eV. \( C_{\text{ch}} \) is
proportional to the density of electronic states and was derived by integrating the transient photocurrent resulting from the photodiode light pulse at short circuit. Figure S9 shows that at a given open circuit voltage the C_μ values are larger for device B than for device F, indicating that the presence of new redox shifts the conduction band edge downward against vacuum.

![Graph](image)

Figure S9 Chemical capacitance derived from transient photovoltage and photocurrent decay measurements. Chemical capacitance (C_μ) from devices B and F as a function of open circuit voltage.

EIS was employed to scrutinize the effect of different redox couples on the dark current, generated under forward bias at the nanocrystalline TiO_2/electrolyte junction through the reduction of oxidized species by conduction band electrons. Under forward bias, electrons are transferred from the FTO substrate into the TiO_2 film, allowing electron propagation through its individual particles, the film resistance being R_f. We have previously demonstrated that any TiO_2 conduction band edge movement induced by the redox couples and additives adsorption can be inferred from tracing the electronic transport resistance (R_t) in the nanocrystalline titania film. [8]

Figure S10 presents the effect of the applied voltage (E_{F,n}−E_{redox}, where E_{F,n} and E_{redox} represent the TiO_2 Fermi level potential and redox potential, respectively) on the transport resistance R_t under dark conditions for the different devices with T_2/T^- or I_3^-/I^- electrolytes. We determined that, for a given R_t value, E_{F,n} is closer to E_{redox} for device B compared to device F, the difference being ~50 mV between the two devices. Taking into account the difference between the electrochemical potential of these
redox couples, the conduction band edge energy level of TiO$_2$ shifts ~100 mV downward in electrolyte containing T$_2$/T$^-$ relative to its value in the presence of I$_3$/I$^-$ containing electrolyte, consistent with results from transient photovoltage decay measurements.

![Figure S10](image)

**Figure S10.** Electron transport resistance derived from transient photovoltage and photocurrent decay measurements. Electron transport resistance $R_t$ of the TiO$_2$ film obtained in the dark at 20 °C as a function of applied forward bias voltage: devices B and F.

The effective electron diffusion length in the DSC device ($L_e = \sqrt{\tau_e D_e}$) can be estimated from using the effective diffusion coefficients and charge recombination lifetimes derived by transient photovoltage and photocurrent decay measurements under illumination conditions with a various bias. Figure S11 compares the electron diffusion length in various devices versus applied bias under 23.8% sun light intensity condition.

![Figure S11](image)

**Figure S11** Electron diffusion length derived from transient photovoltage and photocurrent decay measurements. Electron diffusion length versus applied bias for the different devices (B, D and F) under a white LED light illumination (23.8 mW cm$^{-2}$).
References: