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Multifunctional Interface Modification of Energy Relay Dye in Quasi-solid Dye-sensitized Solar Cells

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In this paper, 4-(dicyanomethylene)-2-t-butyl-6(1,1,7,7-tetramethyljulolidyl-9-enyl)-4H-pyran (DCJTB) has been used in interface modification of dye-sensitized solar cells (DSCs) with combined effects of retarding charge recombination and Förster resonant energy transfer (FRET). DCJTB interface modification significantly improved photovoltaic performance of DSCs. I–V curves shows the conversion efficiency increases from 4.27% to 5.64% with DCJTB coating. The application of DCJTB with combined effects is beneficial to explore more novel multi-functional interface modification materials to improve the performance of DSCs.

Since 1991, dye-sensitized solar cells (DSCs) have attracted much attention worldwide due to its lower production cost and easier fabrication[1]. Much work has been done on dye molecules[2,3], photoanode[4], electrolyte[5] and counter electrode[6] to improve the photovoltaic performance of DSCs. Now the highest conversion efficiency over 12% has been achieved[7].

In DSCs, the interface between sensitized TiO_2 and electrolyte plays a vital role in the photovoltaic performance[8,9] as several important reactions or processes occur here, such as electron injection, charge transfer, charge recombination and dye regeneration. Interface modification and additives in electrolyte have been demonstrated effective ways to enhance the conversion efficiency and improve the stability of DSCs[10–15]. Earlier studies focused mainly on control and modification of metal oxide[14] or carboxylate[13]. Such work improved the performance of DSCs mainly through retarding the charge recombination. Recently, a new kind of interface modification material has been developed to improve the performance of DSCs, which acts as energy relay dye (ERD) that could enhance the photoresponse through Förster resonant energy transfer (FRET) effect, in addition to retarding surface charge recombination[16].

FRET involves dipole–dipole coupling of ERD and acceptor through an electric field, which has been applied in DSCs and polymer solar cells to enhance their photoresponse and obtained excellent results[17]. FRET also occurs between quantum dots and organic dyes, which improves the photo capture[18–20]. Excitation of ERD could be non-radiative transfer to the acceptor dye through the electric field as the emission spectrum of the ERDs overlaps with the absorption spectrum of acceptors[21–23]. FRET efficiency between ERDs and acceptors mostly depended on the Förster radius (R_0). ERDs applied in DSCs were commonly dispersed in the liquid electrolyte[24]. In such a configuration, many ERD molecules cannot transfer energy effectively as they were far away from the acceptor dyes attached on the TiO_2 surface. Furthermore, the solvent could cause the ERDs elicitation quenching. Assembling ERDs on the interface would avoid such disadvantages as they are concentrated at the interface of sensitized photoanode and electrolyte[25–26]. The distance between ERDs and acceptors is short and the contact of ERD and solvent in electrolyte is minimized or avoided as well.

In this paper, 4-(dicyanomethylene)-2-t-butyl-6(1,1,7,7-tetramethyljulolidyl-9-enyl)-4H-pyran (DCJTB) has been applied as ERD in DSCs, which was widely used in organic light emitting diode (OLED)[27], but has never been explored in DSCs. N3 dye was used as the acceptors. Absorption peak of N3 well overlapped with the emission peak of DCJTB, assuring the effective FRET between them. Using DCJTB in the interface modification, photovoltaic performance of DSCs has been improved due to DCJTB's combining effects of FRET and retarding charge recombination.

Experimental

The TiO_2 colloid was prepared with a hydrothermal method, which has been well documented in the previous report[28]. To prepare porous TiO_2 film, transparent conductive FTO glass (12Ω square^{-1}) was thoroughly cleaned and a thin compact TiO_2 film (about 8 nm in thickness) was subsequently deposited on the FTO by dip coating in order to improve ohmic contact and adhesion between the following porous TiO_2 layer and the conductive FTO glass. The doctor blade technique was then adopted to prepare the porous TiO_2 layer, the thickness of the porous layer being controlled by an adhesive tape. Afterwards, the film was thermo-treated at 450°*C* for 30 *min*. When cooled to 110°*C*, the TiO_2 electrode was sensitized by immersion in 0.3 *mmol* L^{-1} N3 absolute ethanol solution for 12 h and cleaning with absolute ethanol. Coating of DCJTB was performed as follows: the saturated ethanol solution of DCJTB was dipping on the sensitized TiO_2 film, then dried in air for 30 min to make it concentrated on the surface of TiO_2 film. The N3 sensitizer was commercially available. DCJTB has been synthesized as in the Ref. 29.

The preparation procedure for the polymer gel electrolytes includes two steps. First, liquid electrolyte was prepared. Second, poly (ethylene oxide) (PEO) was slowly added into the liquid electrolyte and heated under strong stirring until the polymer gel electrolyte became homogeneous. The composition of the liquid electrolyte is as follows: 0.1 *mol* L^{-1} LiI, 0.1 *mol* L^{-1} I_2, 0.6 *mol*L^{-1} 1,2-dimethyl-3-propyl imidazolium iodide (DMPII), and 0.45 *mol*L^{-1} N-methyl-benzimidazole (NMBI). The solvent was 3-methoxypropionitrile (MePN)[30]; the weight ratios (versus liquid electrolyte) for the PEO in the electrolyte was 10.0%.

A chemically platinized conductive glass was used as the counter electrode. When assembling the DSCs, the polymer gel electrolyte was sandwiched by a sensitized TiO_2 electrode and a counter electrode with two clips; the space between the two electrodes was controlled by an adhesive tape with a thickness of 30 *μm*. Finally, the DSCs were baked at 80°*C* to ensure the polymer could penetrate into the nanoporous electrode.

The UV-Vis reflectance absorption spectra were measured with a Hitachi U-3010 spectroscope. The Photocurrent-voltage (I–V), EIS, IMVS and IMPS were investigated by ZAHNER CIMPS electrochemical workstation. The incident photon-to-current conversion efficiency (IPCE) was measured by using a lab-made IPCE setup in Professor Meng's laboratory in Institute of Physics, Chinese Academy of Sciences.

Results and discussion

Figure 1 shows the UV-vis absorption spectra of N3, DCJTB and emission spectrum of DCJTB in solutions and adsorbed on TiO_2 film. One can see from Figure 1(a) that the emission peak of DCJTB differed from the adsorption peak of N3 in the solution, which are 620 nm and 530 nm, respectively. However, Figure 1 (b) reveals that the emission peak of DCJTB shifts to 560 nm when assembled on the TiO_2 surface, which is the same situation in the DSCs devices as using the dip-coating method to concentrate ERD at the interface of photoanode and electrolyte. Such a good overlap would promote effective FRET between them. The shift of emission peak could be attributed to the aggregation or close assembly of the DCJTB molecules on the surface of TiO_2 film. Besides, the emission peak of DCJTB on the TiO_2 surface also becomes much narrower, which is due to the aggregation-induced emission effect[31].

The Förster radius (R_0) is the distance that FRET is 50% probable between ERD and acceptors. It could be calculated using equation (1)[32].

$$R_0^6 = \frac{9000 * \ln(10)\kappa^2 Q_D}{128 * \pi^5 n^4 N_A} \int F_D(\lambda)\varepsilon_A(\lambda)\lambda^4 d\lambda \qquad (1)$$

Where n is the index of refraction of the host medium, κ^2 is the orientation factor (2/3 for random orientation, which could be used

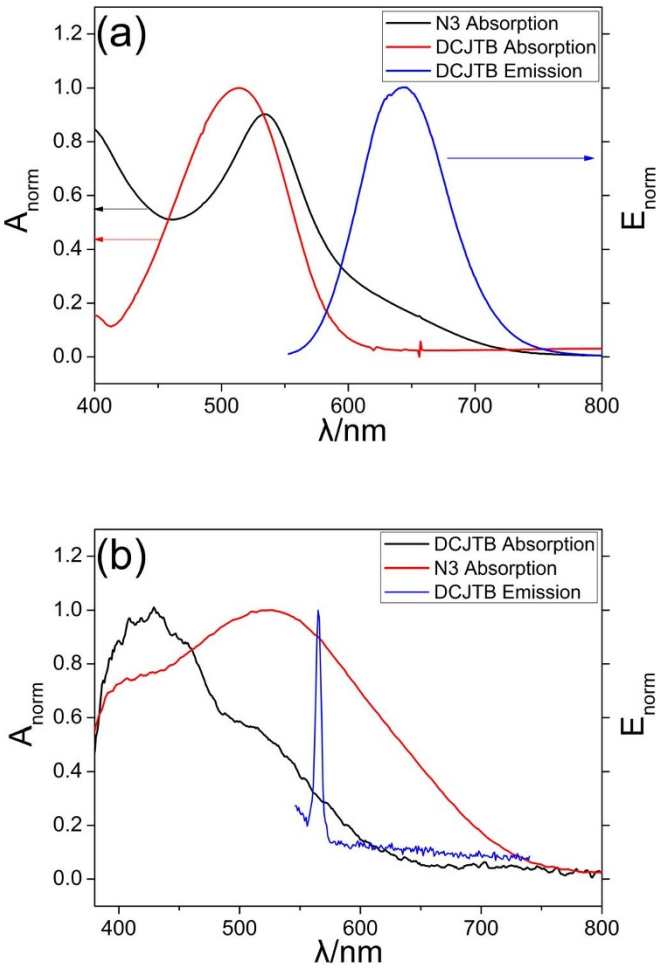

Figure 1 | UV-vis absorption spectra of N3, DCJTB and emission spectrum of DCJTB (a) in solutions and (b) on TiO_2 film.

in DSCs system), N_A is Avogadro's number, Q_D is photoluminescence efficiency of ERDs, and *FD* is the emission profile of the donor. $\varepsilon(\lambda)$ is the molar absorption coefficient at certain wavelength[32]. For the DCJTB/N3 system, it could be calculated the R_0 is 5.2 nm.

The rate of FRET between isolated chromophores has been known as point to point transfer. It is given by equation[32]:

$$k_{FRET} = k_0 * \frac{R_0^6}{r^6} \qquad (2)$$

where r is the separation distance between ERDs and acceptors, k_o is the Boltzmann constant and R_o is the Förster radius calculated from Eq 1. Equation (2) reveals that with a given R_o, r is the most important factor that determines the efficiency of FRET[32].

As shown in Figure 2 (a), adding N3 into the DCJTB solution, the emission intensity decreased to about 47.8% of the initial value. It indicates that the excitation of DCJTB has been partly transferred to N3. However, the efficiency of FRET between DCJTB and N3 is not high enough due to the much larger distance between N3 molecules and DCJTB than R_0 calculated from equation (1) in the solution system. Besides, emission peak of DCJTB and absorption peak of N3 does not overlap so well, as shown in Figure 1(a). Figure 2 (b) reveals that the emission of DCJTB almost disappeared totally when assembled on the surface of TiO_2 film, suggesting much higher energy transfer efficiency than that in the solution. It could be explained that on TiO_2 surface the distance of DCJTB and N3 has been shortened as they both are assembled on the same surface. As a result, the FRET efficiency has been enhanced significantly. Thus, the dip-coating method, which concentrates ERD and acceptors on the

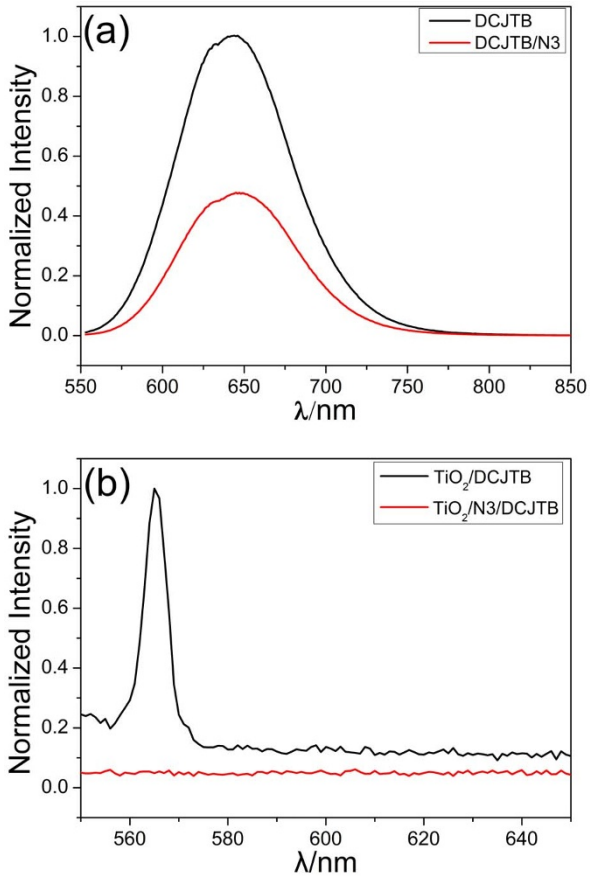

Figure 2 | (a) fluorescence emission spectra in solution (b) fluorescence emission spectra on TiO_2 film of DCJTB and DCJTB/N3.

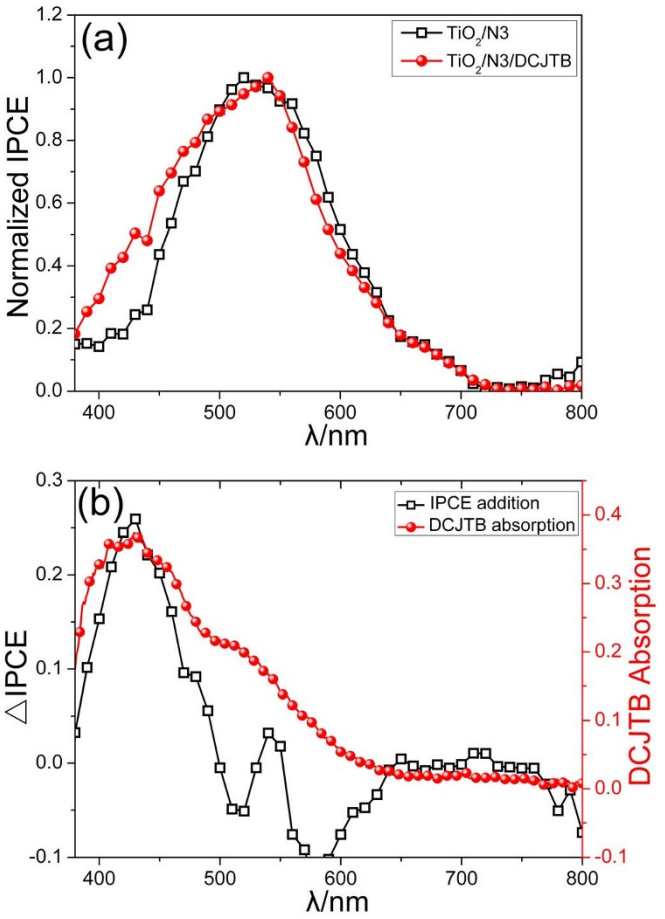

Figure 4 | (a) IPCE spectra of DSCs with and without DCJTB coating (b) comparison between additional IPCE and absorption of DCJTB.

surface of TiO_2 photoanode, has been used to obtain a better FRET efficiency in DSCs. Figure 3 shows the schematic drawing of FRET in DSCs using DCJTB as ERD and N3 as acceptors. The excitation of DCJTB transfers to N3 through FRET, and subsequently the electrons injects to the conductive band of TiO_2, which could increase the photoresponse and photocurrent of DSCs.

As DCJTB molecules are concentrated on the surface of sensitized TiO_2, shortening the distance between ERD and acceptors. Thus the FRET could occur more effectively than that with dispersing ERDs in the electrolyte reported in previous studies[33–34]. Figure 4 (a) shows that with DCJTB coating on the sensitized TiO_2 film, IPCE of DSCs increased clearly in the range of 380–500 nm. This increase is attributable to the effective FRET from DCJTB to N3. And then the additional electrons of N3 inject into the conductive band of TiO_2, which could increase the photocurrent of DSCs. As revealed in Figure 4 (b), additional IPCE with DCJTB coating in the range of 380–500 nm overlaps well with the absorption peak of DCJTB. This result further indicates that FRET from DCJTB to N3 in DSCs system effectively occurred on the sensitized TiO_2 film.

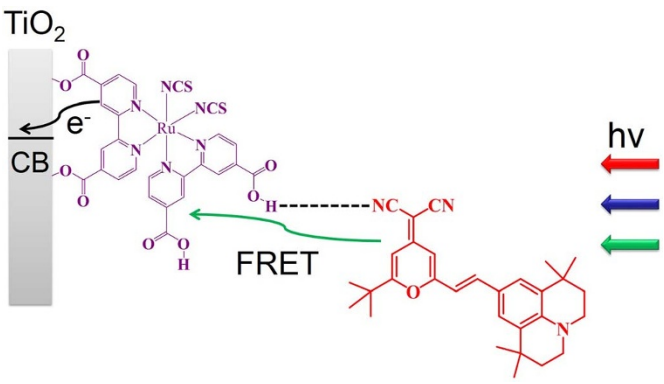

Figure 3 | Diagrammatic drawing of FRET in DSCs using DCJTB as ERD.

The results of IPCE show that the FRET between DCJTB and N3 increased photoresponse of DSCs devices, which could enhance the photocurrent. To investigate the effects of FRET on the DSCs' photovoltaic performance, we tested the I–V curves of DSCs without and with DCJTB coating. As shown in Figure 5 (a) and Table 1, the J_{sc} increases from 12.96 without DCJTB coating to 16.63 mA/cm^2 with DCJTB coating, i.e., 28.3% enhancement in short-circuit current density. It accords with the increase of IPCE shown in Figure 4. The power conversion efficiency of DSCs with DCJTB coating was found to be increased to 5.64% from 4.27%, or relative enhancement of 32%. In the early studies reported in literature[33–34], the increased power conversion efficiency was mainly due to the increased J_{sc} caused by FRET between ERD and acceptors, while V_{oc} remained unchanged or even decreased. However, the present study revealed an appreciable increase in open circuit voltage, V_{oc}, from 0.65 V to 0.69 V with DCJTB coating as shown Figure 5(a) and Table 1. Figure 5 (b) also showed that the dark current density appreciably decreased with DCJTB coating, indicating that the charge recombination at the electrode and electrolyte interface in DSCs was hindered by the insertion of DCJTB coating, as a barrier layer which retards the charge recombination in DSCs as its higher LUMO energy level than that of N3 as shown in Figure 6[35–36]. To further explore the effect of retarding charge recombination in DSCs with DCJTB coating, EIS has been tested.

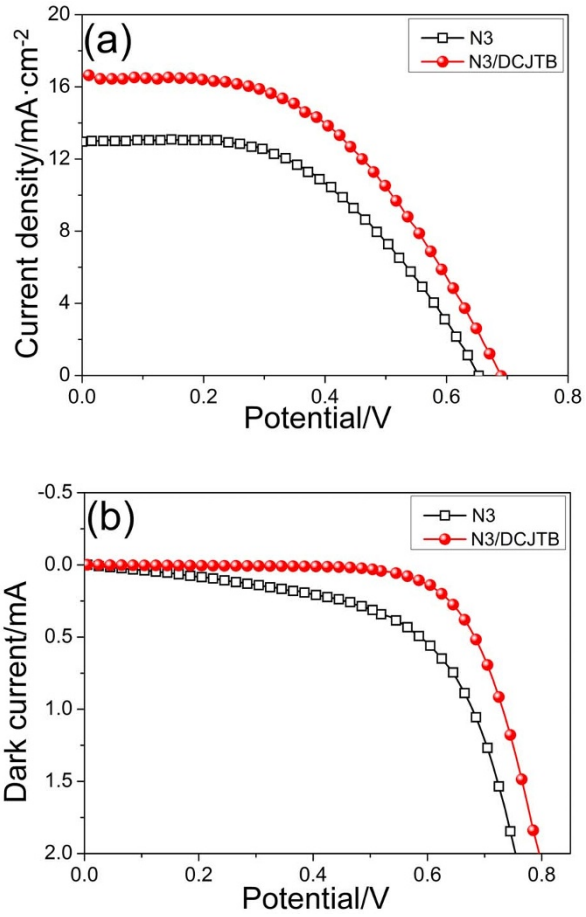

Figure 5 | (a) I–V curves under illumination of 100 mW cm^{-2} (b) Dark current curves of DSCs with and without DCJTB coating.

As shown in the equivalent circuit inserted in Figure 7 (a), the impedance associates with the charge transfer process occurring at Pt counter electrode/electrolyte interface is determined in the frequency range of 10^5–10^3 Hz, which is characterized by the charge transfer resistance (R_1) and the capacitance (CPE_1). In the middle frequency range of 10^3–10^0 Hz, the impedance representing the charge recombination process at the TiO_2/dye/electrolyte interface is described by R_2 and the CPE_2. In the low frequency range or 0.1–10 Hz, the Warburg diffusion impedance (Z_w) within the electrolyte is estimated. Z_w accounts for a finite length Warburg diffusion while CPE represents the constant phase element[37–40].

As DCJTB has been concentrated at the interface of sensitized TiO_2 and electrolyte, we focused on its effects on the charge recombination at such interface (R_2). As shown in Figure 7 (a), the charge recombination resistance increases with DCJTB coating. Thus the back reaction in DSCs has been decreased. Such result also accords with the higher V_{oc} and lower dark current shown in Figure 5. Figure 7 (b) shows the Bode pots of DSCs based on photoanode without and with DCJTB coating. The three peaks in the phase of the spectrum are associated with three transient processes in the DSC. The middle-frequency peak (in the 10–100 Hz range) is determined by the lifetime of the electrons in TiO_2, which is also the charge recombination time in dark condition. It is shown as follow equation[41]

$$\tau_r = \frac{1}{2\pi f_{\min}} \quad (3)$$

As shown in Figure 7 (b), it can be calculated that the charge recombination time of DSCs without and with DCJTB coating are 10.01 ms

Table 1 | Photovoltaic parameters of DSCs with and without DCJTB coating

Samples	J_{sc}/mA/cm^2	V_{oc}/V	FF%	PCE/%
N3	12.96	0.650	50.4	4.27
N3/DCJTB	16.63	0.690	49.1	5.64

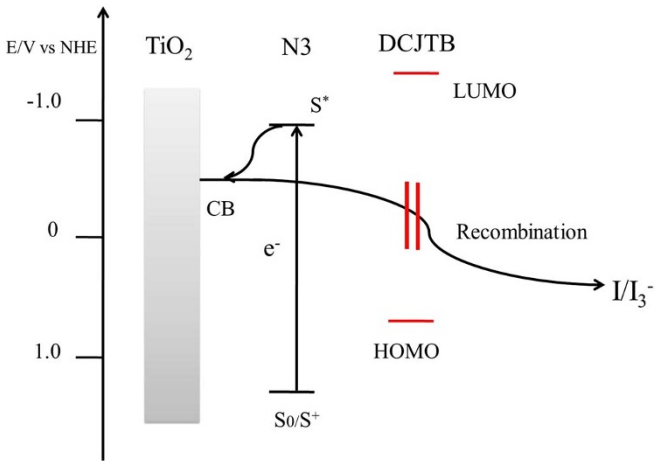

Figure 6 | Diagrammatic drawing of retarding charge recombination of DSCs with DCJTB coating.

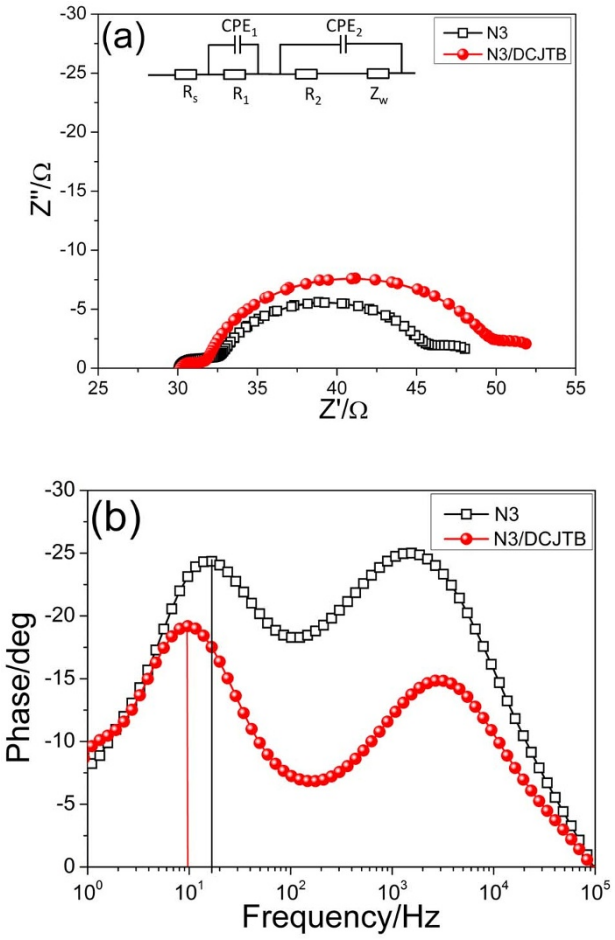

Figure 7 | (a) Nyquist plots under dark condition (b) bode plots of DSCs with and without DCJTB coating.

and 17.1 ms, respectively. As a result, it further indicates that DCJTB could retard the interface charge recombination in DSCs devices. The V_{oc} of DSCs could be expressed by following equation[42–43]:

$$V_{oc} = \frac{RT}{\beta F} \ln\left(\frac{AI}{n_0 k_b [I_3^-] + n_0 k_r [D^+]}\right) \quad (4)$$

where R is molar gas constant, T is temperature in Kelvin, F is Faraday constant, β is the reaction order of I_3^- and electrons, A is the electrode area surface, I is the incident photon flux, n_0 is the concentration of accessible electronic states in the conduction band. k_b and k_r are the kinetic constant of the back reaction and the recombination. $[I_3^-]$ and $[D^+]$ are concentrations of triiodide and oxidized dye, respectively. It could be considered that f_{min} is as same as the back reaction constant (k_b)[44]. Thus from equation (4) it can be obtained that the longer charge recombination time causes the higher V_{oc}. It explains the increased V_{oc} shown in Figure 5 (a) and Table 1.

To further explore the influence of the DCJTB interface modification on the electron diffusion and lifetime in DSCs under illumination, IMVS and IMPS spectra of DSCs with and without DCJTB coating have been tested. IMVS tests the same intensity perturbation but measures periodic modulation of the photovoltage giving the information of electron lifetime under open-circuit conditions at a given illumination intensity. Figure 8 (a) shows the results of IMVS test. It indicates that the electron lifetime has been increased when the DCJTB coating was introduced to the device, in a good agreement with retarding charge recombination as discussed earlier. IMPS measures the periodic photocurrent response to a small sinusoidal perturbation of the light intensity superimposed on a larger steady background level, which could provide information of the dynamics of charge transport and back reaction under short circuit conditions under certain illumination intensity[44].

D_{eff} which represents the effective diffusion coefficient of electrons can be determined by the followed equation[45]

$$D_{eff} = D_0 \times \left(n_{free}/n_{total}\right) \quad (5)$$

where n_{free} is the density of free electrons in the conduction band of TiO_2, and n_{total} is the total density of free and trapped electrons.

As shown in Figure 8 (b), the electron diffusion coefficient of device with DCJTB coating clearly increases compared to that without DCJTB coating. It indicates that DCJTB coating is beneficial for electron transportation in DSCs. Such results also accord with the higher J_{sc} in DSCs based on DCJTB coating, which is shown in Figure 5 (a) and Table 1. It could be due to the increased electron injection and decreased electron quenching and recombination, which increase the free electron in the photoanode. The increased electron injection is due to FRET between DCJTB and N3.

To weigh the electron transport and recombination properties, charge collection efficiency (η_{coll}) derived from IMPS and MVS measurements was apparently considered as meaningful parameter. In sensitized solar cells, η_{coll} can be calculated by the followed equation[46]

$$\eta_{coll} = 1 - \tau_c/\tau_d \quad (6)$$

where τ_c is the electron collection time given by IMPS test and τ_d is the electron lifetime given by IMVS test. Figure 8(c) shows the charge collection efficiency of DCSs without and with DCJTB coating under different illumination intensity. It reveals that the charge collection efficiency increases with DCJTB coating, indicating it is beneficial to charge collection in photoanode of DSCs.

Conclusions

DCJTB as interface modification material has been used in DSCs, and it acts as a barrier layer retarding the charge recombination and resulted in increased photoresponse and electron injection efficiency due to the FRET at the interface of sensitized TiO_2 and electrolyte. Dip-coating method used in interface modification avoided electron quenching by concentrate ERD and acceptors on the surface of sensitized TiO_2. When DCJTB assembled on the surface of TiO_2, the distance between ERD and acceptors was reduced and thus, a higher FRET efficiency was achieved. With combining effects of retarding the charge recombination and FRET, DCJTB interface modification has significantly improved the photovoltaic performance of DSCs.

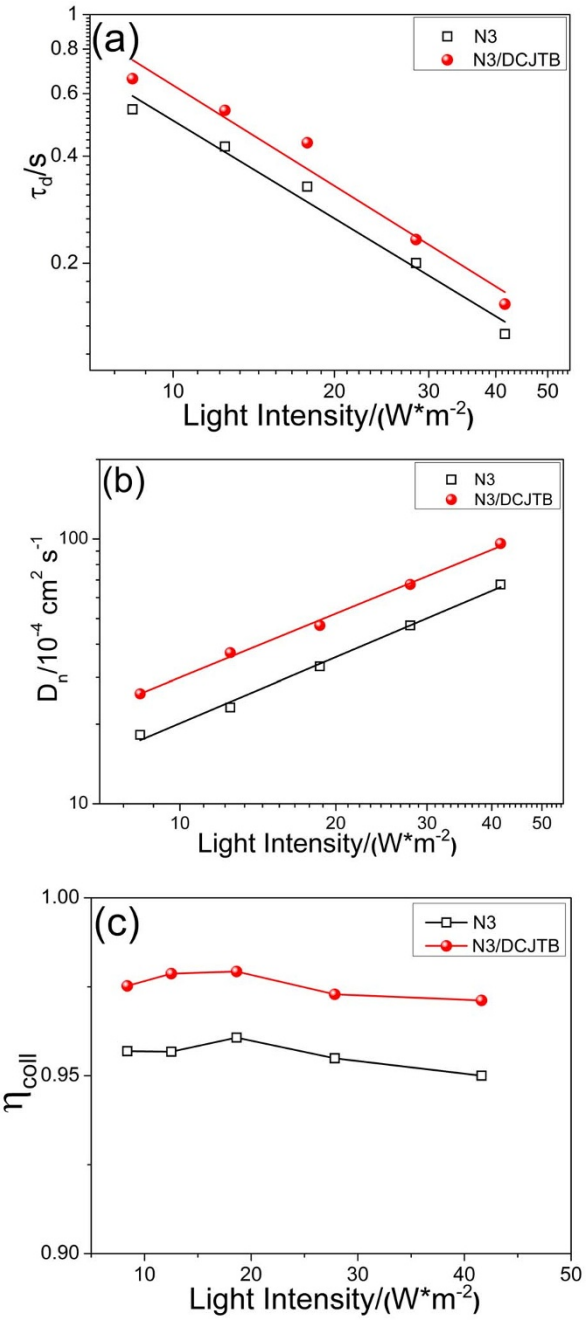

Figure 8 | (a) IMVS (b) IMPS spectra and (c) electron collection efficiency of DSCs with and without DCJTB coating.

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Author contributions

L.W. proposed the conceptual idea and provided financial support through grant application. G.R. participated in the analysis of results, discussing and writing the manuscript. Y.C. and X.L. participated in discussing the results and in writing the manuscript. All authors read and approved the final manuscript.

Additional information

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