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Properties of chromophores determining recombination at TiO₂-dye-electrolyte interface

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Abstract

Different classes of chromophores have been developed for the dye solar cell (DSC), including as the two main classes, organometallic dyes, with Ru-based complexes and Zn-porphyrin complexes, and metal-free dyes. They result in different behavior of recombination by electron transfer at titania/dye/electrolyte, where the dye molecule plays a pivotal role. We present an overview of the main factors that control recombination depending on dye structural and electronic properties: the substituent's nature, the size and nature of the π -bridge, type of absorption onto titania surface, the structure of donor electron moiety or anchoring group. Different recombination mechanisms arise, including direct recombination to redox electrolyte and through dye cation intermediate.

1. Introduction

Due to the need to find alternative energy sources, during the last decade high interest has been developed in the photovoltaic energy. The dye solar cells (DSC) research has been carried out all around the world and it has lead to the improvement of the device efficiency.¹ Amongst various strategies to improve the capacity of dye-sensitized solar cells to convert sunlight to electrical power, successful molecular engineering of photosensitizers has remarkably contributed to the progress of performance of this photovoltaic technology. Generally, an elaborately engineered photosensitizer is supposed to meet several requirements like long time and temperature stability, good anchoring capability,^{2, 3} good optical density,⁴ fast electron injection,⁵⁻⁷ strong absorption in the visible and near infrared spectra and good energy level orbital position respect to the redox electrolyte and semiconductor.³ All these parameters are extremely important and must be optimized at the same time in order to obtain good DSC performance. In this context, special care has to be taken to construct photosensitizers featuring desirable electronic and steric properties. A general problem that still remains is the detailed understanding of the titania/dye/electrolyte interface, because there are some controversial ideas about how the dye structure can interact with the rest of the components of the cell under illumination, like coadsorbents,⁸ redox shuttle⁹⁻¹¹ and electrolyte components, and how these interactions affect the cell performance.

In this feature article, we describe recent progress on the role that the dye structure plays in the recombination process that influences the overall conversion efficiency of the cells. We consider the correlation between dye structure (mainly focused on the donor and electron-rich conjugated bridging groups), and electron transfer rate, either to the redox electrolyte, to the oxidized dye molecule, or to an intermediate binding oxidized state of dye redox shuttle. We comment on the suggested mechanism to account for the kinetics of charge transfer, and how these electron transfer rates affect the value of the open-circuit voltage (V_{oc}) and the overall power conversion efficiency.

2. The structure and function of dyes in DSC

Dye molecules play a pivotal role in DSC, they are involved in light harvesting and

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5 electron injection to the titania, therefore a large part of the final efficiency is associated
6 to them. A classification of dyes could be summarized in two dominant blocks, (1)
7 organometallic dyes, with Ru-based complexes,¹² Zn-porphyrin complexes^{1, 13-15} as the
8 most representative sensitizers and (2) metal-free dyes¹⁶⁻¹⁸ where are included dyes
9 without any transition metal in its structure (Figure 1).
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13 The most extendedly used dyes have been ruthenium bipyridyl dyes that provide
14 both large efficiency and good stability. In the present state of the DSC technology
15 ruthenium dyes may find limitations for a large scale up and future devices
16 commercialization, like sensitization time needed, associated to the low molar extinction
17 coefficient and also the fact that Ru is not an abundant material, and the expensive
18 purifications treatments that are necessary to process pure Ru-based dyes. Another
19 important issue is that the structure of Ru based dyes is difficult to modify in order to
20 increase the light harvesting to higher wavelength and better overlap with the sun
21 spectra. Nonetheless well established Ru dyes like N719 (*cis*-diisothiocyanato-bis (2,2'-
22 bipyridyl-4,4'-dicarboxylato) ruthenium(II) bis(tetrabutylammonium) continue to be a
23 benchmark for successful and stable operation of DSC devices.
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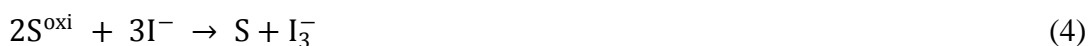
26
27 In the last decade many efforts have been focused on different dye structures without
28 transition metals in the molecule or in porphyrin structures with or without metals
29 (being Zn the most common metal used), aiming at increased overlap with the solar
30 spectra, as well as to reduce the cost of the dye and by extension the cost of the final
31 product as an advantage over Ru dyes. Massive efforts were invested in designing push-
32 pull dyes featuring various electron donors, including triarylaminines,^{16, 19-21} carbazoles,²²
33 indolines,²³⁻²⁸ heteroanthracenes (e.g. phenothiazine),^{29, 30} bis-dimethylfluoreneaniline
34 like JK-1 and JK-2 dyes from Ko et al.¹⁶ and others. These developments achieved
35 better overlap with the solar spectra, cheap fabrication routes, high extinction
36 coefficient, low sensibilization time, etc. With optimization of other cell components
37 such as redox shuttle, efficiencies up to 12.3% for laboratory devices under AM 1.5
38 conditions have been obtained.¹
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42 The use of metal-free dye structures as sensitizers for DSC is related with new or
43 different problems, like aggregation issues and specially the increase in the
44 recombination processes,³¹ which is directly connected with the observed decrease in the
45 value of the open circuit voltage.³²⁻³⁴ It is well known that within typical donor- π
46 conjugated linker-acceptor chromophores (D- π -A) for DSCs, the electronic and steric
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traits of the electron donor play a dominant role to determine the molecular energy levels. The dye features also affect the physicochemical interactions of multiple components at the titania/dye/electrolyte interface, which have profound effects on the ultimate power output of a DSC.³⁵ Such structural properties are intimately correlated with the light harvesting capacity of a photosensitizer and with the operation of some dynamic processes such as exciton dissociation and dye regeneration.

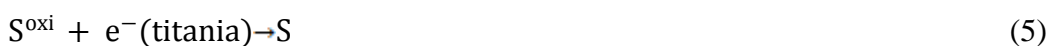
3. Photovoltaic performance of DSC

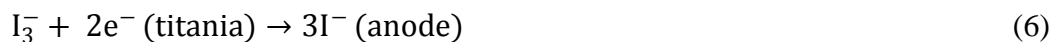
The DSC device is a complex system wherein three different components, the semiconductor, the chromophore and the electrolyte are brought together to generate electric power from light without suffering any permanent chemical transformation. Figure 2a³⁶ shows the operating principles of the DSC and all the processes that take place under illumination, that constitute a regenerative and stable photovoltaic energy conversion system. These processes can be expressed by means of the following reactions



The first step is the absorption of a photon by the sensitizer S [Eq. (1)], leading to the photoexcited sensitizer S^* which injects an electron into the conduction band of the semiconductor, leaving the sensitizer in the oxidized state S^{oxi} [Eq. (2)]. The injected electron flows through the semiconductor network to arrive at the back contact and then through the external load to the counter electrode to reduce the redox mediator [Eq. (3)] which in turn regenerates the oxidized sensitizer [Eq. (4)] which process completes the electrochemical circuit.

Some undesirable reactions resulting in losses in the cell efficiency occur. They are the recombination of the injected electrons either with oxidized sensitizer [Eq. (5)] or with the oxidized redox couple at the TiO_2 surface [Eq. (6)].





Understanding of the processes in a complete device has been achieved using a range of methodologies that have been reviewed recently.^{6,37,38} The total efficiency of the dye-sensitized solar cell depends on optimization and compatibility of each of these constituents, in particular on the semiconductor film along with the dye spectral responses. A very important factor is the high surface area and the thickness of the semiconductor film which leads to increased dye loading, thus optical density is increased resulting in efficient light harvesting.³⁹ Solar photon energy to electricity conversion efficiency is given by the expression.

$$\eta = \frac{j_{sc} \cdot V_{oc} \cdot FF}{\Phi} \quad (7)$$

Here j_{sc} is the short circuit photocurrent density, FF the cell fill factor (Figure 2b) and Φ the power flux of the incident light; usually AM 1.5G illumination (100 mW cm^{-2}) or 1 sun. The incident photon to current conversion efficiency (IPCE) is an important parameter of the solar cell which directly measures how efficiently the incident photons are converted to electrons.

Electron charge transfer processes in DSC can be analyzed by several approaches^{13, 32} and techniques,^{31, 40} such as Impedance Spectroscopy (IS), electron injection dynamics that allows monitoring of the rise of the oxidized dye formed after electron injection,⁴¹ and transients measurements that are carried out with tunable femtosecond laser pulses as a pump-probe technique for studying ultrafast electron transfer reactions.^{42, 43}

In recent years we have developed many studies of IS method^{13, 40, 44} which has the advantage to provide information of the physical processes determining the performance at each required single point of the current density-voltage (jV) curve of the DSC at specified illumination conditions. Using appropriate models developed for DSC analysis⁴⁰ it is possible to determine and isolate the recombination resistance (R_{rec}) from other resistive parameters in the cell. The R_{rec} relates to the recombination flux and it is a key performance-determining parameter in the photovoltaic device. Viewing R_{rec} with respect to the voltage (Fermi level in the TiO_2 film), a relation can be established between charge transfer resistance and the titania/dye/electrolyte interface to clarify the influence of the dye structure in recombination,^{13, 31} which enables improvement of the

dye design.

4. Recombination or electron charge transfer in DSC

The loss of electrons in the TiO₂ electron conductor to the hole carrier, i.e., recombination processes 8 and 9 of Figure 2c, that take place at the interface TiO₂/dye/electrolyte, is severely affected by properties of the materials and the surface conditions. It has been observed that some otherwise efficient dyes increase the recombination rate,⁴⁵ and recombination also produces a strong limitation for solid-state OMeTAD cells.²²

Early work indicated that the kinetics of the back-electron-transfer reaction from the conduction band to the oxidized sensitizer follow a multiexponential time law, occurring on a microsecond to millisecond time scale depending on electron concentration in the semiconductor and thus the light intensity.^{4, 6} Recombination of electrons in TiO₂ with acceptors in the electrolyte is normally quantified by the electron lifetime (τ_n)⁴⁶ and R_{rec} .⁴⁴ Lifetimes observed with Γ/I_3^- are very long (1-20 ms under one sun light intensity) compared with other redox systems used in DSC, explaining the success of this redox couple.

The electron travelling through the mesoporous TiO₂ film, normally formed by nanometer-sized anatase particles, remains within only a few nanometers distance of the semiconductor/electrolyte interface. Recombination of electrons with either oxidized dye molecules or acceptors in the electrolyte is therefore a major factor of electron dynamics in the DSC. With Ru-dyes, the dominant recombination pathway is recombination through the electrolyte because the electron charge transfer to the oxidized dye is negligible due to the molecule dye structure with good spatial separation between injected electrons and the oxidized dye.⁴⁷ This is achieved by the electron donating thiocyanate ligands which shift the distribution of the highest occupied molecular orbital (HOMO) on the oxidized dye away from the reacting TiO₂ surface and reducing the recombination rate accordingly.⁴⁸ However, when using metal-free dyes, it was observed that the overall recombination rate was higher and mainly attributed to the residual oxidized dye, because HOMO is delocalized along the structural backbone between the binding moiety and the remainder of the dye^{7, 21, 49, 50} as can be observed in Figure 3 for diverse dyes using DFT study. This common distribution of the HOMO level generates a stabilization of the intermediate in the dye regeneration process as has

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5 been described in the literature, so the regeneration reaction may proceed via oxidized
6 dye-iodide intermediate state,^{13, 31, 45, 51} creating a new path to the electron
7 recombination. Such behavior produces typically a large decrease in the total charge
8 transfer resistance in the case of some metal-free dyes versus ruthenium dyes. Those
9 metal-free dyes generally are sensitizers without bulky substituents in the structure or
10 with large expansion of the π -conjugated system that limits the packing. All of these
11 processes that appear with the use of metal-free dyes without blocking effect create
12 significant limitations in terms of recombination compared to organometallic dyes.^{52, 53}

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The limitation, differences in the recombination, due to the molecular structure needs
a deeper study to clarify the guidelines to design and synthesize the perfect dye or at
least dyes that present good injection and low recombination. With this goal, the
complete characterization of a DSC using IS and transient absorption measurements
gives us information about the electronic processes that take place at the interfaces
following photogenerated carrier injection and can be related with individual DSCs
components for a future design optimization. Some examples are described below.

Recombination to the electrolyte

From the point of view of the dye structure design, the charge recombination
between the injected electrons in the conduction band (CB) of TiO₂ and the redox
mediator (iodine or cobalt complexes electrolyte) can be effectively reduced by
inhibiting the approaching of ions to the TiO₂ surface (Figure 4) using steric
impediments in the dye molecule.^{9, 10, 35, 54}

The introduction of hydrophobic long alkyl and alkoxy chains on donor moiety or on
 π -bridges such as triphenylamine unit is effective to block the approach of hydrophilic
redox ions to the TiO₂ surface and consequently to suppress the charge recombination,
resulting an increase of the electron lifetime and V_{oc} value (Figure 4b), as demonstrated
by Wang et al.⁵⁵ with C225-C226-C227 dyes from Figure 1, using
cyclopentadithiophene moiety and two 3-hexylthiophene units on π -bridges (Figure 5).
The transient absorption measurements and recombination resistance measured by IS
indicate that the charge recombination between oxidized dye molecules and titania
electrons is stepwise decelerated with the cyclopentadithiophene unit approaching the
electron donor. Similar result has been demonstrated recently³⁵ in solid-state DSC with
three new organic D- π -A sensitizing dyes, WN1, WN3 and WN3.1, where the alkyl

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5 chains on the electron-rich bridge of the dye and also in the electron donor part play a
6 significant role in the suppression of recombination, with a relationship between
7 recombination lifetime and the number of hexyl chains.
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10 It has also been proposed that a compact dye sensitizer layer on TiO₂ surface is
11 important to reduce the charge recombination between TiO₂ and redox couple.⁵⁶⁻⁵⁸ Such
12 layer can also prevent the recombination to the oxidized dye molecules as reported by
13 Mori et al. for DSC based on coumarin dyes.⁵⁹ Recombination rate has been measured
14 for zinc porphyrin complexes like those represented in Figure 1 named YD0 and YD2,
15 where YD2 consists on a diarylamino group with two hexyl chains attached to the
16 porphyrin ring acting as an electron donor, π -conjugated phenylethynyl group as a
17 bridge, and the carboxylic acid moiety as an acceptor. The porphyrin chromophore itself
18 constitutes the π bridge as a light-harvesting center in this particular D- π -A structure,
19 and YD0 does not have the diarylamino substituent as a bulky donor and serves as a
20 reference dye to test the effect of the electron donor in the recombination. It was
21 observed that effectively the recombination resistance for YD2 is similar to a
22 commercial Ru dye N719 (Figure 6) because the diarylamino group plays a key role to
23 repel the triiodide ions from the titania surface and near oxidized dye. The charge
24 recombination rate of YD2 is significantly less compared with that YD0, which impacts
25 increasing the V_{oc} value.¹³ These results confirm that a good synthesis design, especially
26 in the donor moiety, that can prevent the redox approach, is crucial to avoid the
27 recombination process to the electrolyte.⁴⁵ For DSC based on D- π -A dye with starburst
28 triarylamine and with D- π -A dye with the simple triarylamine²⁰ it has been reported that
29 the starburst-shape dye sensitizers show better performances than rod-shape sensitizers
30 by blocking charge recombination between TiO₂ and the triiodide ion.^{56, 58, 60}
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47 The introduction of sterically hindered substituents often causes not only the twist
48 between π -bridges but also the decrease in the amount of adsorbed dye on the TiO₂
49 surface, resulting in the reduction of the light harvesting efficiency and of the number of
50 the injected electrons. Additionally, the expansion of π -conjugated system³¹ can no
51 longer form a compact blocking layer (larger surface coverage),¹⁸ resulting in faster
52 charge recombination and lower V_{oc} (Figure 7) as has been shown in our previous
53 studies³¹ with oligithienylenevinylene dyes (FL n) and also demonstrated by Hagfeldt et
54 al.¹⁸ (Figure 8) using the family of dyes shown in Figure 1 (L0, L2 and L3 dyes). It was
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4 shown that the recombination to the electrolyte is effectively controllable by the
5 modification of dye molecular structure: the introduction of hydrophobic alkyl chains
6 and bulky substituents to dye molecular structure discourages the recombination to the
7 redox couple, leading to increased V_{oc} .^{17, 28}

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11 It is also important to mention that the presence of deoxycholic acid (DCA) or
12 chenodeoxycholic acid (CDCA) in organic based systems has been shown to improve
13 the voltages,⁸ an effect often attributed to DCA/CDCA retarding recombination between
14 injected electrons and electrolyte, through blocking effects.
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19 Related with retarding recombination to the redox media, Diao et al.⁶¹ demonstrate
20 that fluorine substituents on the donor part of the ruthenium complexes produce a
21 slowing down of charge recombination. Similar results have been found with metal-free
22 sensitizers.^{62, 63} In both cases, it is possible to argue that effect the surface of the TiO_2
23 can be protected from the electrolyte by the negatively charged of F increasing the V_{oc}
24 due to an upward shift of potential and a retardation of charge recombination. The same
25 effect is reported by Berlinguette et al.⁶⁴ using S in the donor part of metal-free dye
26 instead of O with an increment in V_{oc} . That effect is similar to the function of NCS
27 groups from the N719 protecting the closer proximity of the electrolyte species to the
28 TiO_2 .
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37 When the redox shuttle is a Co (II)/Co (III) complex similar effects are observed. For
38 N719, the efficiency decreases drastically due to a possible formation of ion-pairs
39 between the negatively charged, TiO_2 /dye and oxidized Co(III) electrolyte decreasing
40 the photocurrent due to lower charge collection efficiency.¹⁰ Nevertheless, Ru dyes that
41 contain long alkyl chain in the structure, like Z907, create a compact dye layer when
42 absorbed on titania, that block the Co (III) redox species approach and a decrease of the
43 photocurrent is not observed. The same effect is observed to metal-free dyes with bulky
44 substituents on the donor part of the structure.^{9, 10, 55, 65}
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51 For I_3^-/I^- redox shuttle the process of recombination through the electrolyte has been
52 widely studied by transient absorption measurements^{11, 42, 66, 67, 43, 53} in order to
53 understand which are the predominant species in redox electrolyte that accelerate the
54 recombination. Meyer et al.⁴² did not find a direct evidence for the reaction between
55 injected electrons into TiO_2 and di-iodide, on DSC based on Ru- bipyridine sensitizers,
56 being the data consistent with charge recombination with I_3^- . However, later work¹¹ find
57 the electron life time correlated with free-iodine (I_2) concentration and independent of
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5 I_3^- concentration, supporting that electron recombination to the electrolyte occurs by
6 iodine reduction instead than reduction of triiodide in the case of N719 and Z907 and
7 also for a squaraine dye VG5⁶⁸ without any steric impediment.
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10 In general an increase in the recombination with DSC based in metal-free dyes
11 without steric impediments is observed, versus DSC based on Ru-dyes, due to a possible
12 increment in the recombination to the oxidized dye molecule (reaction 8 in Figure 2c)
13 that is added to the already established to the redox mediator.
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18 **Recombination to the oxidized dye molecule**

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20 The recombination through the oxidized dye can be interpreted in two different ways;
21 (1) acceleration of recombination by dye molecule structure that induced electron
22 transfer to the electrolyte due to poor titania surface blocking or (2) recombination via
23 oxidized dye stabilization, then the recombination electrons regenerate the dye
24 molecule. The extent to which these effects occur depends on the nature of the dye
25 molecule, and usually metal-free dyes without bulky substituents show the largest
26 influence of these effects.
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32 As has been commented previously, if the dye molecule strongly influences the rate
33 constant for recombination to electrolyte acceptor species, the recombination increment
34 can be assigned to the influence of the dye on the local concentration of oxidized redox
35 couple adjacent to the TiO₂ surface,^{13, 52} a possible dipole effect create by the dye
36 molecule or changes in the polarizability^{69, 70} and even to a bound complex between
37 redox and oxidized dye.^{49, 67, 71} In the second possibility, an electron-deficient
38 substituent in the dye molecule could increase the charge recombination through the
39 oxidized dye molecule due to the favorable electron affinity.
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46 It has also been demonstrated that the electron affinity of the substituent in the dye
47 structure has a strong influence on dye properties, especially if there are electron-
48 deficient substituent or electron-rich substituent-like ethyl groups.⁵⁵ Although the
49 modification of the substituent has a relatively small impact on the titania conduction
50 band edge, it has a remarkably large effect in the charge transfer recombination process.
51 There is a decrease in recombination reaction order for the cells made from electron-rich
52 substituent chromophores versus their counterpart with electron-deficient substituent.
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58 The influence of the substituents in the recombination to the oxidized dye has been
59 also studied recently in a carbazole-type fluorescent dyes.⁷² In these dyes carboxyl
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5 groups on different positions on the chromophore skeleton induce not only electron
6 injection from the excited state to the CB of TiO₂, but also the recombination process
7 between the electrons injected to the CB of TiO₂ and the oxidized dye. The high
8 energetic electron injection yield and the retardation of the charge recombination to the
9 oxidized dye are lower for dyes which are functionally separated into an anchoring
10 group for attachment on TiO₂ surface and an electron acceptor moiety. These features
11 are responsible for the high j_{sc} comparable to that of the D- π -A dye sensitizer where
12 carboxyl group acts both as the anchoring group for attachment on TiO₂ surface and as
13 electron acceptor. The general idea applied here is that the conjugated part or linker
14 between donor and acceptor groups is the critical moiety of the dye molecule. The linker
15 must have the HOMO level distributed, to avoid the recombination increase due to a
16 possible interaction between iodine and oxidized cation.^{1, 31, 48} and also must be separate
17 from the acceptor unit, to be far enough from the titania surface. The addition of large
18 groups that create steric impediment to redox electrolyte approach to the titania surface,
19 in the donor or linker part of the structure, is also convenient. One critical point is the
20 substituent in the linker, because if it is electron-deficient then the electron charge
21 transfer rate from the injected electrons in the semiconductor through oxidized dye state
22 increases, with a decrease in the V_{oc} of the cell and consequently lowering the DSC
23 efficiency.
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39 Conclusions

40 Recombination in DSCs presents different mechanisms depending of the dye nature
41 and redox couple. It is generally observed that cells based on metal-free dyes reveal
42 important differences of the interfacial factors determining recombination, with respect
43 to the cells based on organometallic dyes. The rate of recombination is higher in metal-
44 free dyes due to the extra recombination to the oxidized dye. Nevertheless, the observed
45 increment could be compensated with optimized molecular engineering development,
46 using bulky electron rich substituents that avoid the recombination through the oxidized
47 dye and also block the redox shuttle from reaching the titania surface. It emerges from
48 this survey that the recombination through the oxidized dye may not be disregarded in
49 the metal-free dyes design and when Co is used as a redox shuttle, because it is a pivotal
50 issue in the total rate of the DSC recombination, directly associated to the performance.
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Figure Captions

Figure 1. Structures of Zn-porphyrin complexes and metal-free dyes. Reproduced from Refs.^{1, 13, 16, 18, 20, 55} with permission.

Figure 2. (a) DSC structure, (b) The fill factor measures the squareness of the I - V curve and (c) schematic DSC where all the process that take place in the solar cell are described.

Figure 3. Optimized chemical structures and frontier molecular orbitals of two metal-free dyes, BG-1 (left) and BG-2 (right), based on thiophene units asymmetrically functionalized by N -aryl carbazole. HOMO distribution (lower) and LUMO distribution (upper).

Figure 4. Scheme of structures of D- π -A dyes.

Figure 5. (A) j - V characteristic of cells made with an iodine electrolyte and organic dyes named C225-C226-C227 with serially varied conjugation orders of a cyclopentadithiophene unit and two 3-hexylthiophene segments. (B) Charge recombination resistance. The dye structures are shown in Figure 1b. Reproduced from Ref⁵⁵ with permission.

Figure 6. Recombination resistance replotted with respect to equivalent common conduction band voltage so that distance between Fermi level and conduction band is the same in all cases

Figure 7. FLN dyes structures; n is the number of thienylvinylene units. Current density-potential curves for DSCs at 1 sun with FLN as sensitizers

Figure 8. (A) Extracted charge as a function of V_{oc} and (B) electron lifetime as function of V_{oc} in dye-sensitized solar cells based on L0, L2 and L3 dyes, sensitized for 16 h using 6 μm TiO_2 and an electrolyte consisting of 0.6 M TBAI, 0.1 M LiI, 0.5 M 4-TBP, and 0.05 M I_2 in acetonitrile. Bare TiO_2 (circles), L0 (square), L2 (triangles), L3

(gray dots). Reproduced from Ref ¹⁸ with permission.

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Figure 1

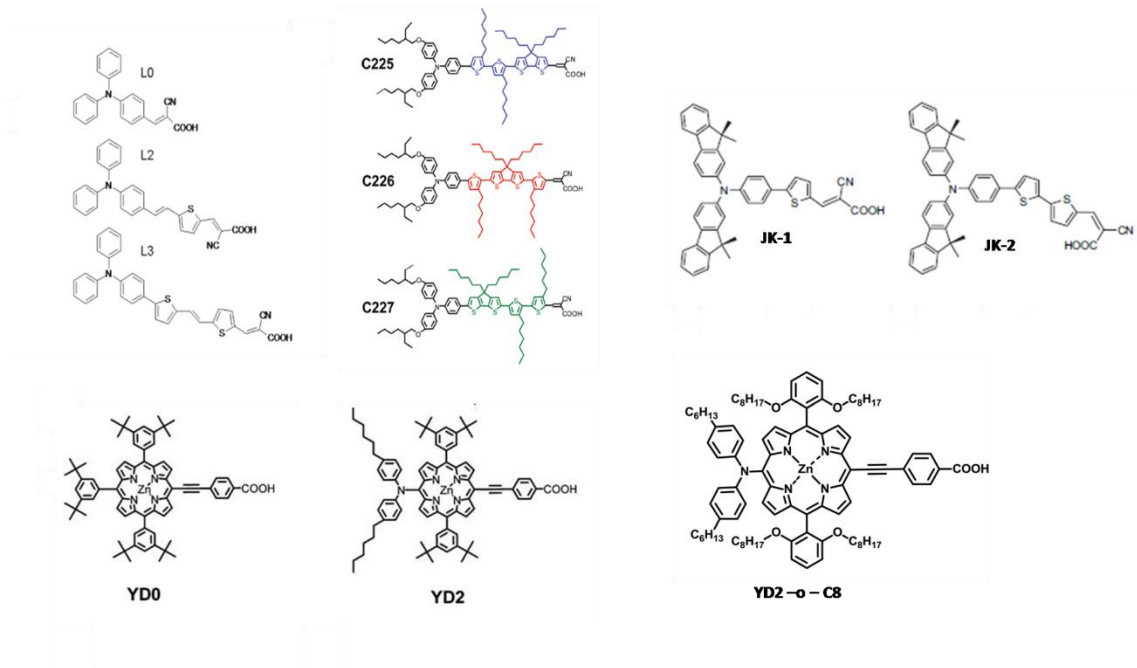


Figure 2

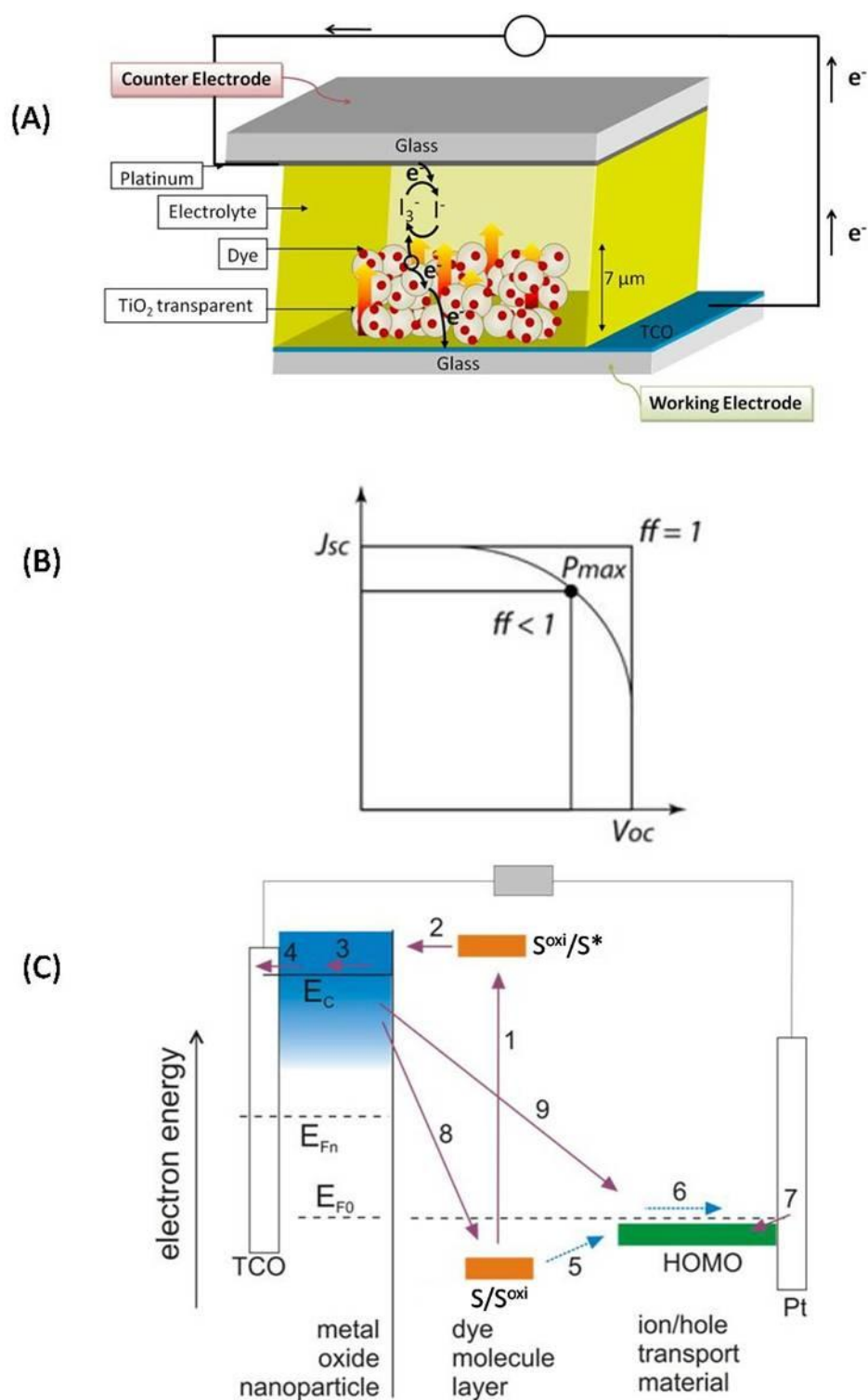


Figure 3

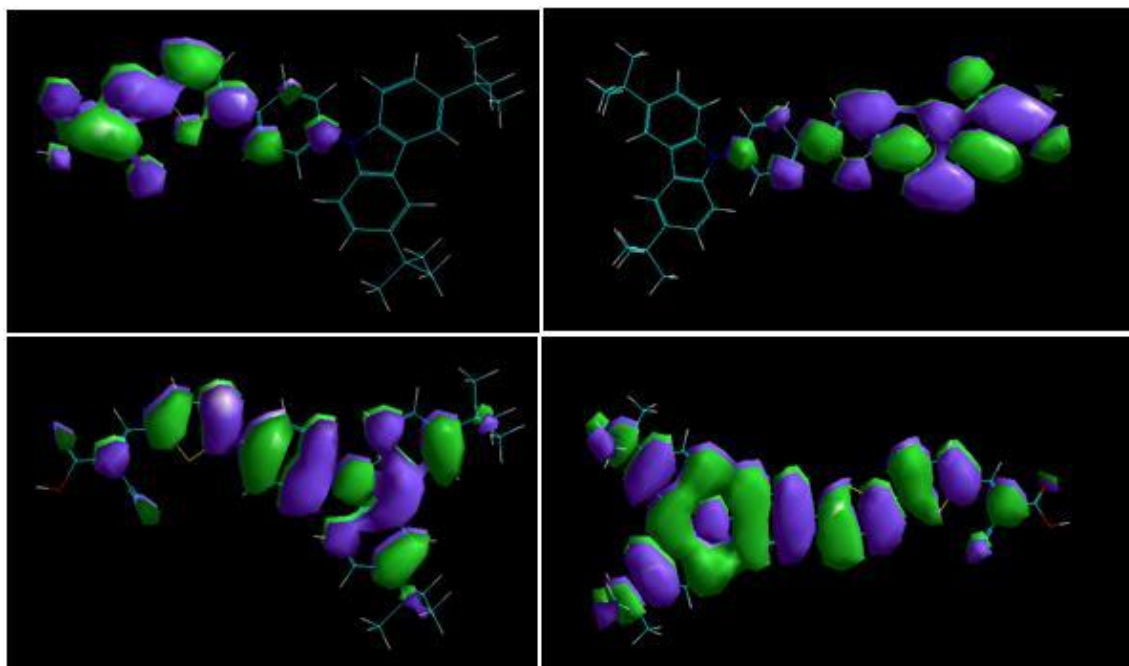


Figure 4

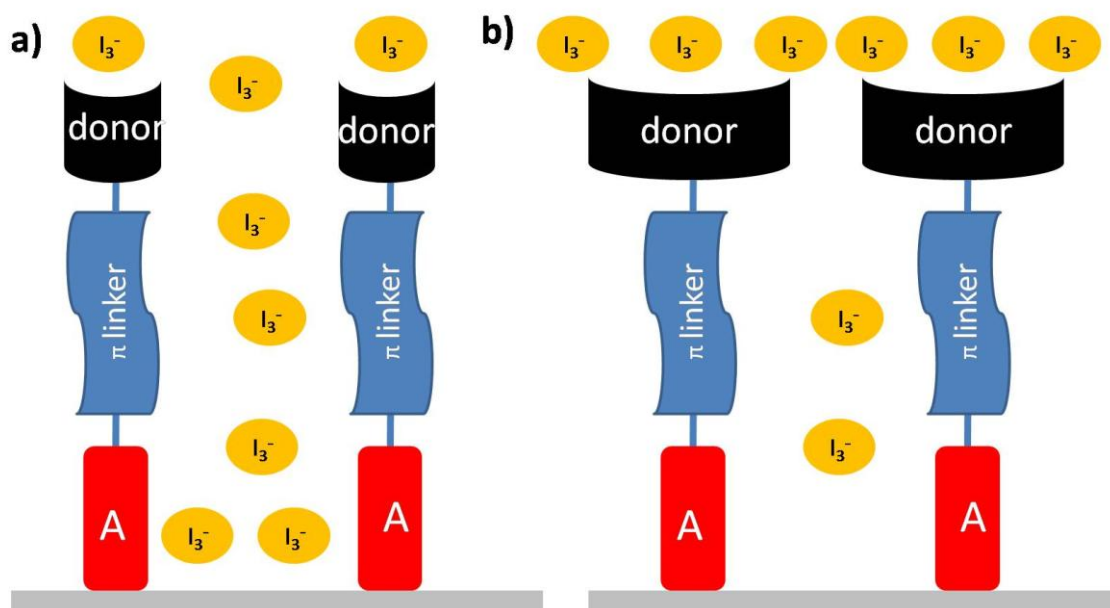


Figure 5

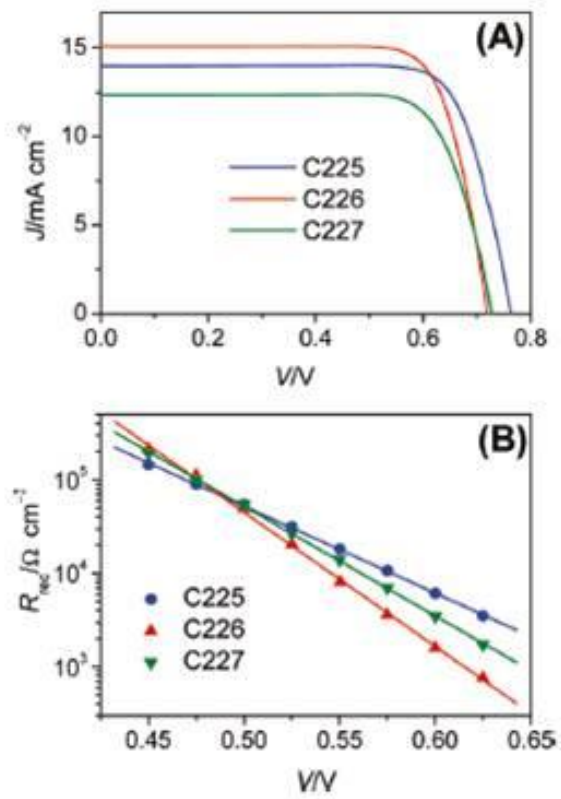


Figure 6

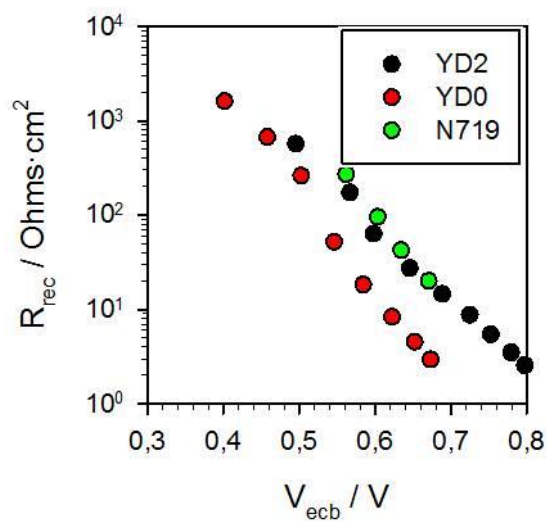


Figure 7

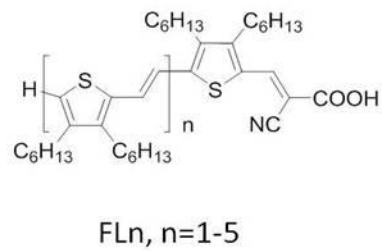
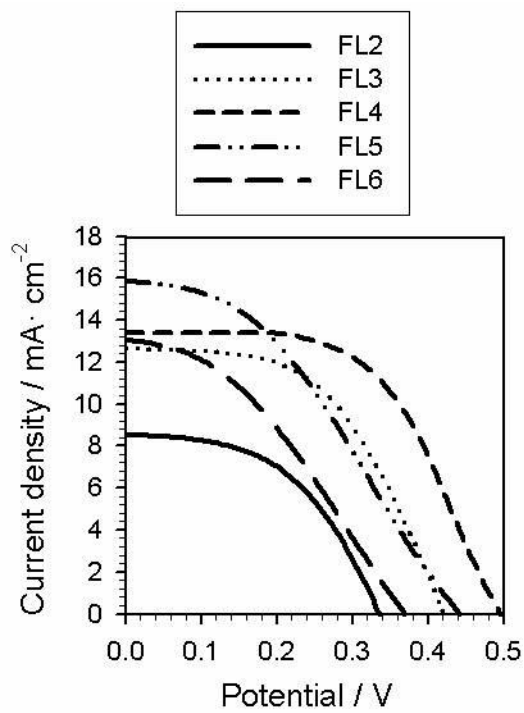
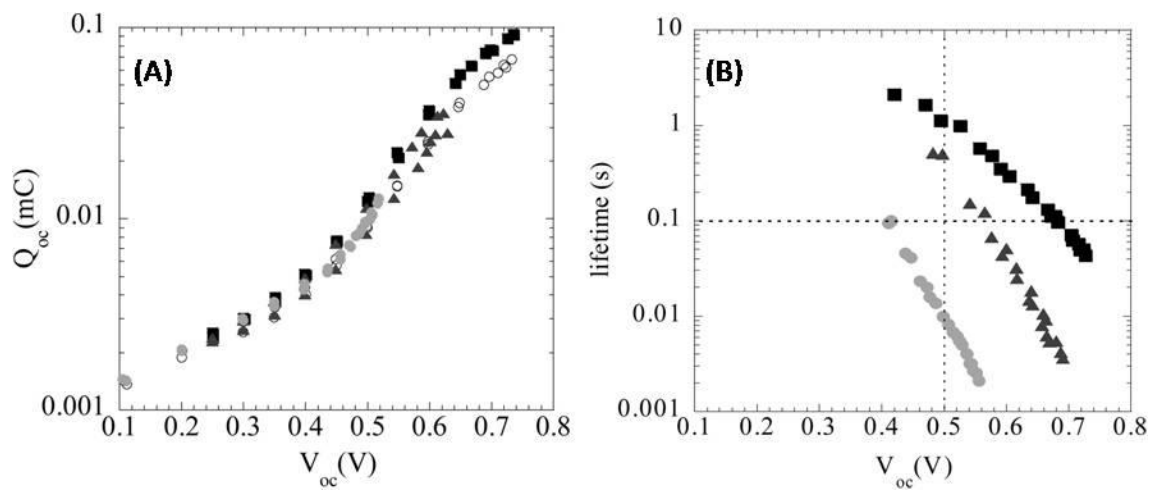
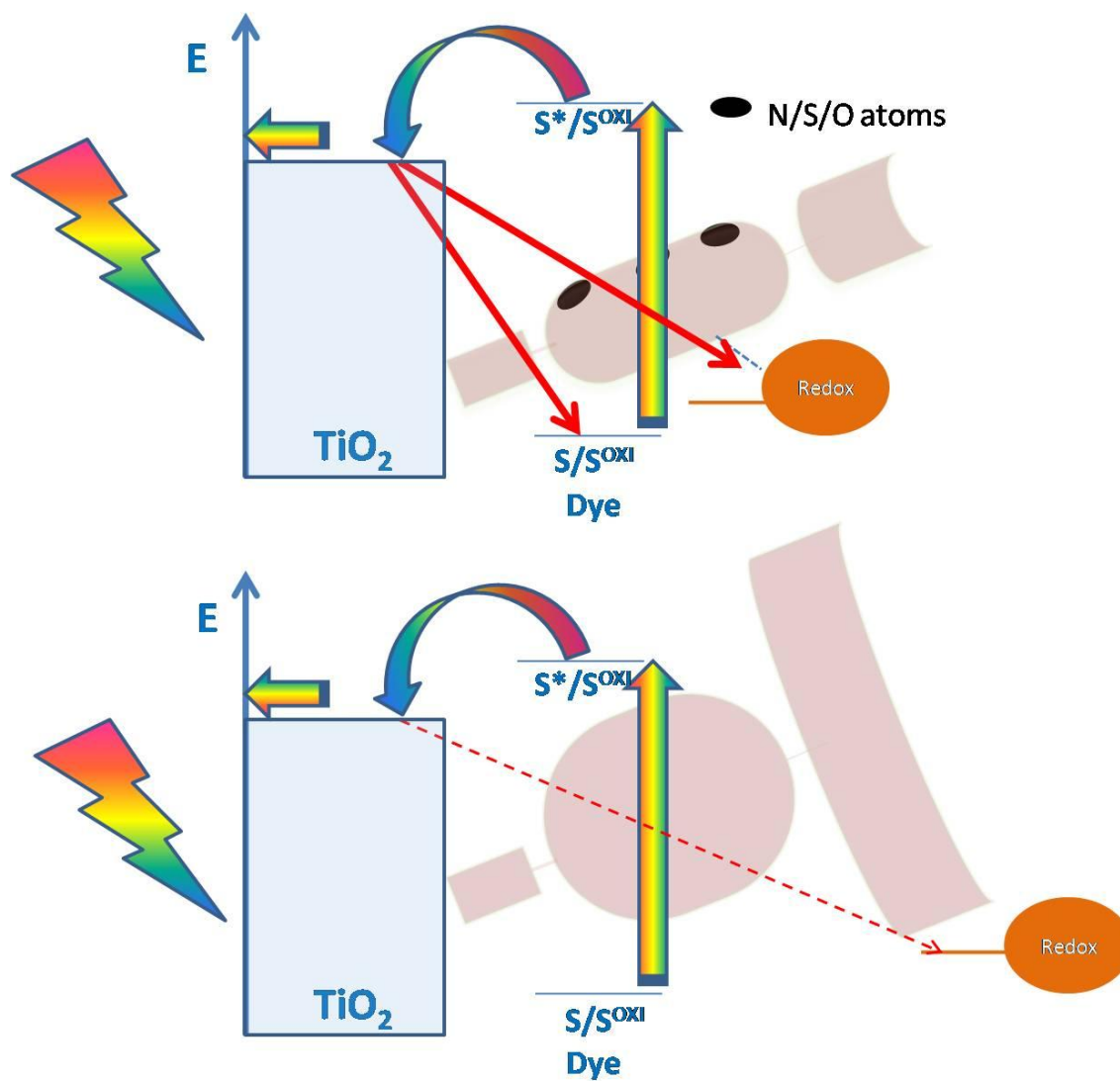


Figure 8



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Eva M. Barea (M. Sc. Chemistry 2000, Ph. D. Chemistry 2005) is assistant professor at Universitat Jaume I de Castelló, she works in Group of Photovoltaic and Optoelectronic Devices of 20 physicists and chemists.

Her research activity is focused on nanoscale devices for production of clean energies, in particular dye-sensitized solar cells and water splitting with visible light and semiconductors.

Barea is specialist in Dye Solar Cells (DSC) fabrication, optimization and characterization by Impedance Spectroscopy. Large experience in synthesis of new semiconductor architectures based on metal oxide and in hydrothermal synthesis. Expertise in study of recombination on DSC based on new organic dyes



Juan Bisquert is a professor of applied physics at Universitat Jaume I de Castelló. He conducts experimental and theoretical research on nanoscale devices for production and storage of clean energies. His main topics of interest are dye- and quantum dot-sensitized solar cells, organic solar cells, and solar fuel production. He has developed the application of measurement techniques and physical modeling that relate the device operation with the elementary steps that take place at the nanoscale dimension: charge transfer, carrier transport, chemical reaction, etc., especially in the field of impedance spectroscopy, as well as general device models.