New Extraction Technique of In-Gap Electronic-State Spectrum Based on Time-Resolved Charge Extraction

Zedong Lin*

ABSTRACT: The in-gap electronic state (trap state) is an important factor that determines the photovoltaic performance of solar cells. In this article, we put forward a new technique for extracting the density of trap state (DOST) distribution based on the time-resolved charge extraction (TRCE) experiment result. Based on strict derivation, we find that when the TRCE result is linear, the extracted DOST distribution is exponential type and vice versa. Compared to the approach given by Wang et al., the method introduced in this paper is more accurate and reliable. Compared to the approach based on the space charge-limited current (SCLC) experiment result, our method needs less computation.

INTRODUCTION

To further enhance the power conversion efficiency (PCE) of solar cells, it is necessary to explore the photovoltaic mechanism such as the carrier transport,\(^1\)\(^{−}\)\(^7\) density of trap state (DOST) distribution,\(^\text{4−7}\) carrier recombination,\(^\text{8−12}\) ion migration,\(^\text{13−17}\) and so on.

The DOST distribution is a crucial topic in the study of solar cells. It affects the carrier recombination\(^8\)\(^{−}\)\(^20\) and the open-circuit voltage,\(^\text{21−23}\) and hinders the PCE enhancement of solar cells.\(^\text{4−7}\)

There are few advances in the method study of the DOST distribution extraction.\(^\text{37}\) The space charge-limited current (SCLC) method\(^\text{28−33}\) is used to determine the DOST distribution based on the measured current density–voltage data at different temperatures. The chemical capacitance model\(^\text{34−36}\) is widely used to investigate the DOST distribution, which can be measured by the technique of impedance spectrum (IS)\(^\text{37}\) and time-resolved charge extraction (TRCE).\(^\text{42−43}\)

This model is adopted to study various photovoltaic systems such as dye-sensitized solar cells (DSSCs), perovskite solar cells (PSCs), and so on,\(^\text{42−48}\) which is widely accepted. Walter et al.\(^\text{37}\) put forward the extraction method of DOST distribution based on the IS experiment result. Using the chemical capacitance model,\(^\text{37}\) they regard the trapping and detrapping of carriers by trap states as the charging and discharging of chemical capacitance \(C(\omega)\), where \(\omega\) is the angular frequency of the ac signal.\(^\text{37}\) They present the formula \(\text{DOST} = (U_{\text{bio}}/eL)(dC/d\omega)/(\omega)\) to calculate the DOST distribution.\(^\text{37}\) Here, \(U_{\text{bio}}\) denotes the built-in electric voltage, \(e\) denotes the elementary charge, \(L\) denotes the depletion width, \(k_B\) denotes the Boltzmann constant. \(\omega = k_B T \ln(\omega_0/\omega)\), where \(T\) denotes the ambient temperature and \(\omega_0\) denotes the attempt-to-escape frequency.\(^\text{37−41}\) Wang et al.\(^\text{42−43}\) reported the DOST distribution extraction technique based on the TRCE experiment result. They use the formula \(\text{DOST} = C_p/edS(1 - p)\) to calculate the

DOST distribution according to the capacitance model.\(^\text{42−45}\)

Here, \(C_p\) denotes the chemical capacitance, \(d\) denotes the film thickness, \(S\) denotes the effective area of the photoanode, and \(p\) denotes the porosity of TiO\(_2\) layer.\(^\text{42−45}\)

The method given by Wang et al. is a simple approach for the extraction of DOST distribution. However, there are some shortcomings in their method. (i) The result extracted by their method is the plot of DOST distribution versus photon-voltage,\(^\text{42,43}\) not the relation of DOST and energy level (DOST distribution). (ii) The formula \(\text{DOST} = C_p/edS(1 - p)\) is put forward from the qualitative physics picture, not based on the strict derivation.\(^\text{45}\) Therefore, there is no certainty that this formula is accurate. In other words, we are not sure that the DOST distribution extracted by their method is accurate. In this paper, we overcome these shortcomings. Based on the chemical capacitance model, we put forward a new technique for calculating DOST distribution based on the TRCE experiment by strict derivation.

RESULTS AND DISCUSSION

Theory and Method. In this section, we establish the method for extracting the DOST distribution based on the TRCE measurement result. According to the chemical capacitance model,\(^\text{42−45}\) the chemical capacitance is contributed by the electrons in the trap states and conductor band, which satisfies

Received: June 13, 2020
Accepted: August 12, 2020
Published: August 21, 2020
Here, $c_{\text{trap}} = e^2 \frac{\partial \delta n_t}{\partial E_{Fn}}$ and $c_{\text{cb}} = e^2 \frac{\partial \delta n_c}{\partial E_{Fn}}$ denote the capacitances contributed by the electrons in the trap states and conductor band, respectively. $n_t$ is the density of trapped electrons and $n_c$ is the carrier density in the conductor band. $E_{Fn}$ denotes the electron quasi-Fermi energy level.

Therefore, we have

$$C_\mu = e^2 \delta(n_t + n_c) / \partial E_{Fn}$$

(2)

For the TRCE experiment, because of the illumination of pulse, the number of extracted electrons from traps is much more than that in the conductor band ($n_t \gg n_c$). Therefore, we can rewrite eq 2 as
The density of trapped electrons $n_t$ satisfies\textsuperscript{42,43}

$$n_t = \int \rho_t(E)f(E)\,dE$$

(4)

Here, $\rho_t(E)$ denotes the DOST distribution and $f(E)$ denotes the Fermi–Dirac distribution of electrons at the corresponding energy level $E$, which satisfies\textsuperscript{42,43}

$$f(E) = \frac{1}{\exp\left(\frac{E - E_F}{k_B T}\right) + 1}$$

(5)

Therefore, we have

$$\frac{\partial n_t}{\partial E_{F_n}} = \frac{\partial}{\partial E_{F_n}} \left( \int \rho_t(E)f(E)\,dE \right)$$

(6)

Substituting formula 5 into formula 6, we have

$$\frac{\partial n_t}{\partial E_{F_n}} = \int \rho_t(E)f(E)(1 - f(E))\,dE$$

(7)

We rewrite formula 7 as

$$\frac{\partial n_t}{\partial E_{F_n}} = \frac{1}{k_B T} \int \rho_t(E)f(E)(1 - f(E))\,dE$$

(8)

Substituting formula 8 into the formula 3, we have

$$C_\mu = e^2 \frac{1}{k_B T} \int \rho_t(E)f(E)(1 - f(E))\,dE$$

(9)

We rewrite formula 9 as

$$\int \rho_t(E)f(E)(1 - f(E))\,dE = \frac{k_B T}{e^2} C_\mu$$

(10)

The TRCE experiment result shows that the equivalent chemical capacitance is a function of the photovoltage.\textsuperscript{42,43}

Therefore, we rewrite eq 10 as

$$\int \rho_t(E)f(E)(1 - f(E))\,dE = \frac{k_B T}{e^2} C_\mu(V_{ph})$$

(11)

Substituting eq 5 into eq 11, we have

$$\int \rho_t(E)\left(1 + \frac{1}{e^2} C_\mu(V_{ph})\right)\,dE = \frac{k_B T}{e^2} C_\mu(V_{ph})$$

(12)

We rewrite eq 12 as

$$\int \rho_t(E)\left(1 - \frac{1}{e^2} C_\mu(V_{ph})\right)\,dE = \frac{k_B T}{e^2} C_\mu(V_{ph})$$

(13)
By defining a probability derivation factor

\[ g(E_{fn} - E) = \frac{1}{\exp\left(\frac{-(E_{fn} - E)}{k_BT}\right) + 1} \]

we rewrite eq 13 as

\[ \int \rho_i(E)g(E_{fn} - E)dE = \frac{k_BT}{\epsilon}C_m(V_{ph}) \]  

Equation 15 is the fundamental equation of our method. Here, \( C_m(V_{ph}) \) can be obtained by the TRCE measurement. Using the absorbance spectrum, Kelvin probe (KP), ultraviolet photoemission spectroscopy (UPS), and X-ray photoelectron spectroscopy (XPS), we get the band gap \( E_g \) and energy-level position of conductor band \( E_c \) Fermi energy-level \( E_{F0} \) and valence band \( E_v \). The left-hand side of eq 15 is the convolution integral of the DOS \( \rho_i \) distribution and the probability derivation factor. We can get the DOS \( \rho_i \) distribution by deconvolution. We solve eq 15 for the DOS \( \rho_i \) distribution adopting the numerical deconvolution ((\( q, r \) = deconv(\( u, v \)) of MATLAB).

Compared to the formula \( DOS_T = C_m/e\delta(1 - p) \) in the method given by Wang et al., eq 15 is put forward based on the strict derivation. Therefore, it is more accurate and reliable to extract the DOS \( \rho_i \) distribution using our method than the method reported by Wang et al. Our numerical method is effective for the photovoltaic system that can be measured by the TRCE technique. Because the TRCE measurement is effective for various photovoltaic systems such as DSSCs, PSCs, and so on, our numerical method is effective for these solar cells. The type of trap states extracted by our numerical method consists of bulk traps, interface traps, and surface traps. The bulk traps and surface traps are almost contributed by the active layer of the device. The interface traps are contributed by the interfaces of device. We can specify the shallow traps and deep traps from the extracted DOS \( \rho_i \) distribution.

**Exponential-type DOS** \( \rho_i \) **Distribution.** We investigate the exponential-type DOS \( \rho_i \) distribution. The exponential-type distribution satisfies the formula:

\[ \rho_i(E) = \frac{N_T}{E_B} \exp\left(\frac{E - E_c}{E_B}\right) \]  

Here, \( E_B \) denotes the characteristic energy. \( N_T \) denotes the total density of the trapped state. Substituting formula 16 into formula 4, taking zero-temperature approximation, we have

\[ n_i = N_T\left(\exp\left(\frac{E_{Fn} - E_c}{E_B}\right) - \exp\left(\frac{E_v - E_c}{E_B}\right)\right) \]  

Therefore, we have

\[ \frac{\partial n_i}{\partial E_{Fn}} = \frac{N_T}{E_B} \exp\left(\frac{E_{Fn} - E_c}{E_B}\right) \]  

According to the relation \( E_{Fn} = E_{Fp} + V_{ph}\epsilon \) we have

\[ \frac{\partial n_i}{\partial E_{Fp}} = \frac{N_T}{E_B} \exp\left(\frac{E_{Fp} + V_{ph}\epsilon - E_c}{E_B}\right) \]

Substituting formula 19 into eq 3, we have

\[ C_{\mu} = \frac{e^2N_T}{E_B} \exp\left(\frac{E_{Fp} + V_{ph}\epsilon - E_c}{E_B}\right) \]

We rewrite formula 20 as

\[ \ln C_{\mu} = \frac{e}{E_B}V_{ph} + \frac{E_{Fp} - E_c}{E_B} + \ln\left(\frac{e^2N_T}{E_B}\right) \]

Equation 21 satisfies the linear mathematical form

\[ \ln C_{\mu} = aV_{ph} + b \]

where \( a = e/E_B, b = (E_{Fp} - E_c)/E_B + \ln(e^2N_T/E_B) \).

For the intrinsic perovskite, the quasi-Fermi energy level satisfies \( E_{Fn} = E_{Fp} + V_{ph}\epsilon/2 \). We have

\[ \ln C_{\mu} = \frac{e}{2E_B}V_{ph} + \frac{E_{Fp} - E_c}{E_B} + \ln\left(\frac{e^2N_T}{E_B}\right) \]

which satisfies the linear mathematical form \( \ln C_{\mu} = aV_{ph} + b \). Here, \( a = e/2E_B, b = (E_{Fp} - E_c)/E_B + \ln(e^2N_T/E_B) \).

Therefore, by strict derivation, we prove that for the exponential-type DOS \( \rho_i \) distribution, the logarithm of chemical capacitance is proportional to the photovoltage (TRCE result). We call it the exponential-type distribution theorem in this paper. Similarly, we also prove the inverse theorem based on strict derivation. Details of the proof are given in the Supporting Information. We can use the inverse theorem to extract the DOS \( \rho_i \) distribution when the TRCE result is linear. We call this method the analytic method below.

To verify the validity of our numerical method, we use both the analytic method and our numerical method to extract the DOS \( \rho_i \) distribution and make a comparison. As shown in Figure 1 a–c, we set \( b = 0.1 \) and \( a \) as 19, 12, and 8.2, respectively. We use the analytic method to calculate \( E_{Fp} \) from Figure 1a–c (shown in Table 1). Using our numerical method reported in this article, we extract the DOS \( \rho_i \) distributions from Figure 1a–c, respectively (see Figure 1d–f). To compare with the result extracted by the analytic method, we use the exponential fitting \((f(E) = e^{\exp(dE)})\) to obtain \( E_B \) (see Table 1). It can be seen from Table 1 that \( E_B \) obtained by our numerical method is in line with \( E_B \) calculated by the analytic method, indicating that the numerical algorithm to do the deconvolution in our calculation is reliable. The slight deviation of \( E_B \) obtained by the two methods is explained as follows: the analytic method is derived based on the zero-temperature approximation, exponential-type DOS \( \rho_i \) distribution, and the chemical capacitance model. Our numerical method is derived based on the chemical capacitance model. Therefore, the slight deviation of \( E_B \) calculated by the two methods is caused by the zero-temperature approximation and the error of exponential fitting.

**Non-Exponential-Type DOS** \( \rho_i \) **Distribution.** We explore the non-exponential-type DOS \( \rho_i \) distribution. The exponential-type distribution theorem can be expressed equivalently as when the TRCE result is nonlinear, the extracted DOS \( \rho_i \) distribution is non-exponential-type (converse-negative proposition of the exponential-type distribution theorem). Because the analytic method is derived based on the hypothesis of the exponential-type DOS \( \rho_i \) distribution, the analytic method is effective for the
DOS$_T$ distribution extraction only when the TRCE result is linear. When the TRCE result is nonlinear, we cannot use the analytic method to extract the DOS$_T$ distribution. The numerical method given in our work is effective for arbitrary TRCE results and can be used to extract the general-type DOS$_T$ distribution. We take the TRCE data in ref 42 as an example. Figure 2 shows the TRCE result for DSSCs. The TRCE data is obtained from ref 42 using Engauge Digitizer software. It can be seen from Figure 2 that the TRCE result is nonlinear.

For the DOS$_T$ distribution extraction of DSSCs, we use the redox energy level of electrolyte $E_{\text{redox}}$ to replace the hole quasi-Fermi energy level $E_{Fp}$. As shown in Figure 3, using our numerical method, we extract the DOS$_T$ distribution from Figure 2. It can be seen that the extracted DOS$_T$ distribution is non-exponential-type, which significantly deviates the exponential fitting.

**Example of DOS$_T$ Distribution Extraction.** We take the TRCE data in ref 43 as an example for further investigation. The TRCE results for DSSCs with small, middle, and large sizes of TiO$_2$ nanoparticles are obtained by Engauge Digitizer software shown in Figure 4a–c, respectively. Using our numerical method reported in this article, we extract the DOS$_T$ distributions from Figure 4a–c, respectively (black dots in Figure 4d–f). We perform exponential-type fittings for the extracted DOS$_T$ distributions (black solid lines in Figure 4d–f) and obtain the characteristic energies (see Table 2). It can be seen that the characteristic energy decreases with increasing TiO$_2$ nanoparticle size. This is consistent with the result extracted by the TPV method reported by Wang et al. 43

**CONCLUSIONS**

In conclusion, to solve the shortcomings in the method given by Wang et al., we present a new technique for DOS$_T$ distribution extraction based on the TRCE experiment. Based on the strict derivation, we prove that when the TRCE result is linear, the extracted DOS$_T$ distribution is exponential type and vice versa. Compared to the TRCE method given by Wang et al., the method reported in this paper is more accurate and reliable. Compared to the SCLC method, our method is much simpler and requires less computation.

**EXPERIMENTAL SECTION**

Time-resolved charge extraction is an effective experimental technique for exploring the DOS$_T$ distribution based on the chemical capacitance model. 42 The details of the TRCE setup can be found in refs 42 and 43. Here, we introduce the mechanism of TRCE measurement. Under the illumination of pulse, the device under the open-circuit condition produces a photovoltage. Due to the carrier recombination, the photovoltage decays. At a specified timing, when the solar cell was switched into the short circuit, the charge extraction was started at the corresponding photovoltage. From the TRCE experiment, we get the plot of the amount of extracted charge versus the photovoltage. 42–45 According to the definition of chemical capacitance $C_p = \frac{dQ}{dV_{ph}}$, we obtain the plot of the chemical capacitance versus the photovoltage (TRCE result). 42–45 We use this result to extract the DOS$_T$ distribution. 42–45

**ASSOCIATED CONTENT**

1. **Supporting Information**

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.0c02800.

**AUTHOR INFORMATION**

**Corresponding Author**

Zedong Lin — Department of Chemistry, Renmin University of China, Beijing 100872, China; orcid.org/0000-0002-7322-7690; Email: zedonglin@ruc.edu.cn

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c02800

**Notes**

The author declares no competing financial interest.

**ACKNOWLEDGMENTS**

The author is grateful to Ning-Hua Tong for his useful comments.

**REFERENCES**

(1) Khan, M. T.; Salado, M.; Almohammadi, A.; Kazim, S.; Ahmad, S. Elucidating the impact of charge selectivity contact in halide perovskite through impedance spectroscopy. *Adv. Mater. Interfaces* 2016, 6, 1901193.

(2) Mäckel, H.; MacKenzie, R. C. I. Determination of charge-carrier mobility in disordered thin-film solar cells as a function of current density. *Phys. Rev. Appl.* 2018, 9, No. 034020.

(3) Juška, G.; Aurlauskas, K.; Viliūnas, M.; Kocka, J. Extraction current transients: new method study of charge transport in microcrystalline silicon. *Phys. Rev. Lett.* 2000, 84, 4946–4949.

(4) Kearney, K.; Seo, G.; Matsushima, T.; Adachi, C.; Ertekin, E.; Rockett, A. Computational analysis of the interplay between deep level traps and perovskite solar cell efficiency. *J. Am. Chem. Soc.* 2018, 140, 15655–15660.

(5) Bai, Y.; Lin, Y.; Ren, L.; Shi, X.; Stroumina, E.; Deng, Y.; Wang, Q.; Fang, Y.; Zheng, X.; Lin, Y.; Chen, Z.; Du, Y.; Wang, L.; Huang, J. Oligomeric silica-wrapped perovskites enable synchronous defect passivation and grain stabilization for efficient and stable perovskite photovoltaic. *ACS Energy Lett.* 2019, 4, 1231–1240.

(6) Li, X.; Wang, K.; Jiang, Y.; Yang, Y.; Cao, X.; Ma, H. Furrowed hole-transport layer using argon plasma in an inverted perovskite solar cell. *New J. Chem.* 2019, 43, 14625.

(7) Cai, F.; Yan, Y.; Yao, J.; Wang, P.; Wang, H.; Gurney, R. S.; Liu, D.; Wang, T. Ionic additive engineering toward high-efficiency perovskite solar cells with reduced grain boundaries and trap density. *Adv. Funct. Mater.* 2018, 28, No. 1801985.

(8) Calado, P.; Burkitt, D.; Yao, J.; Troughton, J.; Watson, T. M.; Carnie, M. J.; Telford, A. M.; O’Regan, B. C.; Nelson, J.; Branes, P. R. F. Identifying dominant recombination mechanisms in perovskite solar cells by measuring the transient ideality factor. *Phys. Rev. Appl.* 2019, 11, No. 044005.

(9) Kirchartz, T.; Pieters, B. E.; Kirkpatrick, J.; Rau, U.; Nelson, J. Recombination via tail states in polythiophene: fullerene solar cells. *Phys. Rev. B* 2011, 83, No. 115209.

(10) Ostroverkhova, O. Organic optoelectronic materials: mechanisms and applications. *Chem. Rev.* 2016, 116, 13279–13412.

(11)Sherkar, T. S.; Momblonba, C.; Gil-Escrig, L.; Bolink, H. J.; Koster, L. J. A. Improving perovskite solar cells: insights from a validated device model. *Adv. Energy Mater.* 2017, 7, No. 1602432.

(12) Ren, X.; Wang, Z.; Sha, W. E. I.; Choy, W. C. H. Exploring the way to approach the efficiency limit of perovskite solar cells by drift-diffusion model. *ACS Photonics* 2017, 4, 934–942.

(13) Senocrate, A.; Moudrakovski, I.; Kim, G. Y.; Yang, T.; Gregori, G.; Gr-tiel, M.; Maier, J. The nature of ion conduction in methylammonium lead iodide: a multimethod approach. *Angew. Chem., Int. Ed.* 2017, 56, 7755–7759.

(14) Yang, T.; Gregori, G.; Pellet, N.; Gratzel, M.; Maier, J. The significance of ion conduction in a hybrid organic-inorganic lead-
iodide-based perovskite photosensitizer. *Angew. Chem., Int. Ed.* 2015, 54, 7905–7910.

(15) Yuan, Y.; Huang, J. Ion migration in organometal trihalide perovskite and its impact on photovoltaic efficiency and stability. *Acc. Chem. Res.* 2016, 49, 286–293.

(16) Eames, C.; Frost, J. M.; Barnes, P. R. F.; O’Regan, B. C.; Walsh, A.; Islam, M. S. Ionic transport in hybrid lead iodide perovskite solar cells. *Nat. Commun.* 2015, 6, No. 7497.

(17) Levine, I.; Nayak, P. K.; Wang, J. T.; Sakai, N.; Van Reenen, S.; Brenner, T. M.; Mukhopadhyay, S.; Smith, H. J.; Hodes, G.; Cahen, D. Interface-dependent ion migration/accumulation controls hysteresis in MAPbI₃ solar cells. *J. Phys. Chem. C* 2016, 120, 16399–16411.

(18) Ran, C.; Xu, J.; Gao, W.; Huang, C.; Dou, S. Defects in metal triiodide perovskite materials towards high-performance solar cells: origin, impact, characterization, and engineering. *Chem. Soc. Rev.* 2018, 47, 4581.

(19) Lakhwani, G.; Rao, A.; Friend, R. H. Bimolecular recombination in organic photovoltaics. *Annu. Rev. Phys. Chem.* 2014, 65, 557–581.

(20) Shekar, T. S.; Mombrola, C.; Gil-Escrig, L.; Avila, J.; Sessolo, M.; Bolink, H. J.; Koster, L. J. A. Recombination in perovskite solar cells: significance of grain boundaries, interface traps, and defect ions. *ACS Energy Lett.* 2017, 2, 1214–1222.

(21) Sandberg, O. J.; Sundqvist, A.; Nyman, M.; Osterbacka, R. Relating charge transport, contact properties, and recombination to open-circuit voltage in sandwich-type thin film solar cells. *Phys. Rev. Appl.* 2016, 5, No. 044005.

(22) Azzoz, M.; Kirchertz, T.; Nelson, J. Factors controlling open-circuit voltage losses in organic solar cells. *Trends Chem.* 2019, 1, 49–62.

(23) Tress, W.; Leo, K.; Riede, M. Dominating recombination mechanisms in organic solar cells based on ZnPc and C₆₀. *Appl. Phys. Lett.* 2013, 102, No. 163901.

(24) Zheng, X.; Chen, B.; Dai, J.; Fang, Y.; Bai, Y.; Lin, Y.; Wei, H.; Zeng, X.; Huang, J. Defect passivation in hybrid perovskite solar cells using quaternary ammonium halide anions and cations. *Nat. Energy* 2017, 2, No. 17102.

(25) Shiba, H.; Nakayama, M.; Kasuga, T.; Grimes, R. W.; Külner, J. Calculation of arrangement of oxygen ions and vacancies in double perovskite GdBaCoO₄₊ₓ by first-principles DFT with Monte Carlo simulations. *Phys. Chem. Chem. Phys.* 2013, 15, 104–116.

(26) Saffari, M.; Moheshtour, M. A.; Soleimani, H. R.; Tagani, M. B. DFT analysis and FDTD simulation of CH₃NH₃PbI₃ crystals: discrete levels induced by oxygen in rubrene. *J. Phys. Chem. C* 2013, 117, 1249–1256.

(27) Kim, J.; Yun, A. J.; Kim, J.; Cho, D.; Kim, S.; Hong, S.; Park, B. Electronic traps and their correlations to perovskite solar cell performance via compositional and thermal annealing controls. *ACS Mater. Interfaces* 2019, 11, 6907–6917.

(28) Wang, Y.; Wu, D.; Fu, L.; Ai, X.; Xu, D.; Zhang, J. Density of state determination of two types of intra-gap traps in dye-sensitized solar cells and its influence on device performance. *Phys. Chem. Chem. Phys.* 2014, 16, 11626–11632.

(29) Wang, Y.; Wu, D.; Fu, L.; Ai, X.; Xu, D.; Zhang, J. Correlation between energy and spatial distribution of intragap trap states in the TiO₂ photoanode of dye-sensitized solar cells. *ChemPhysChem* 2015, 16, 2253–2259.

(30) Bisquert, J.; Vlkhenko, V. S. Interpretation of the time constants measured by kinetic techniques in nanostructured semiconductor electrodes and dye-sensitized solar cells. *J. Phys. Chem. B* 2004, 108, 2313–2322.

(31) Bisquert, J. Chemical diffusion coefficient of electrons in nanostructured semiconductor electrodes and dye-sensitized solar cells. *J. Phys. Chem. B* 2004, 108, 2323–2332.

(32) Bisquert, J. Chemical diffusion coefficient of electrons in nanostructured semiconductor electrodes and dye-sensitized solar cells. *J. Phys. Chem. B* 2004, 108, 2323–2332.

(33) Bisquert, J. Chemical diffusion coefficient of electrons in nanostructured semiconductor electrodes and dye-sensitized solar cells. *J. Phys. Chem. B* 2004, 108, 2323–2332.