Charge transport in dye-sensitized solar cell*

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Abstract

The effect of charge transport on the photovoltaic properties of dye-sensitized solar cells (DSCs) was investigated by the experimental results and the ion transport. The short current photocurrent density ($J_s$) is determined by the electron transport in porous TiO$_2$ when the diffusion limited current ($J_{diff}$) due to the $I^-_3$ transport is larger than the photo-generated electron flux ($J_{ph}$) estimated from the light harvesting efficiency of dye-sensitized porous TiO$_2$ and the solar spectrum. However, the $J_s$ value is determined by the ion transport in the electrolyte solution at $J_{diff}<J_{ph}$. The $J_s$ value becomes constant against light intensity, and is expressed as the saturated current ($J_{sc}$). The $J_s$ value depends on the thickness ($d$) of the TiO$_2$ layer, the initial concentration ($C_{I_3}^0$), and the diffusion coefficient ($D_{I_3}$) of $I^-_3$. These suitable parameters were determined by using the ion transport.

Keywords: Dye-sensitized solar cells, TiO$_2$, charge transport, diffusion, electrolyte, iodide

Mathematics Subject Classification: 5.00, 5.04, 6.04

1. Introduction

Dye-sensitized solar cells (DSCs) have received much attention because of their high energy-conversion efficiency ($\eta = 12\%$) and low cost of production [1–3]. A DSC as shown in figure 1 is composed of a dye adsorbed porous TiO$_2$ film on transparent conductive oxide (TCO) glass, an electrolyte solution containing an $\Gamma$/$I^-_3$ redox couple, and a counter electrode (CE). After light absorption of a dye, the electron is injected from the excited state of the dye to the conduction band of TiO$_2$. The oxidized dye is reduced by iodide ions ($\Gamma^-$) in the electrolyte solution. The ions such as $\Gamma^-$ and $I^-_3$ transport through the porous TiO$_2$ and bulk phase of the electrolyte solution. The oxidized $\Gamma^- (I^{-}_3)$ is reduced to $\Gamma^-$ on the surface of the CE. The injected electron also diffuses through the porous TiO$_2$ and reaches to the TCO glass.

The leakage of the electrolyte solution is the main problem for the application of DSCs because the electrolyte solution is liquid. Many approaches for long time stability have been carried out by introduction of polymers, TiO$_2$ particle, and non-volatile solvents [3–12]. Ionic liquids have been also utilized as the electrolyte in DSCs for improvement of the durability because of the properties of high thermal stability, very low vapor pressure and non-flammability [5–9]. However, the photovoltaic performance of DSCs based on these stabilization techniques of the electrolytes is lower than that based on the normal volatile electrolyte. Especially, the photocurrent density of DSCs based on ionic liquid is lower than that based on volatile solution. The photocurrent is dominated not only by the charge injection from a dye to TiO$_2$, but also by the charge transports of electrons, $\Gamma^-$ and $I^-_3$ . The ion transport rate in ionic liquid is generally slower than that of volatile solution. The lower photocurrent must be due to the slower ion transport. Therefore, the charge transports need to be discussed to explain the mechanism of $J_{sc}$ and to find the suitable condition.

2. Experimental

1-propyl-3-methylimidazolium iodide (MPImI) was used as an ionic liquid electrolyte. All electrolytes were prepared by dissolving 0.6 M 1,2-dimethyl-3-propylimidazolium iodide (DMPImI), 0.03–0.26 M I$_2$, 0.05 M LiI, and 0.3 M 4-tert-butylpyridine (TBP). The viscosity of the electrolytes was measured by Viscotech Co., Ltd A carbazole dye with hexylsubstituted oligothiophene, MK-2 (Soken Chemical & Engineering Co., Ltd, Tokyo, Japan) [13] was used as a...
sensitizer. Transparent nanocrystalline TiO2 films were prepared as follows. TiO2 films were formed by screen printing method. The TiO2 paste (Nanoxide-20N, JGC catalysts and Chemicals Ltd) was printed on a transparent conducting oxide (TCO) glass substrate (F-doped SnO2, sheet resistance 10.Ω cm-2, Nippon Sheet Glass), followed by sintering at 500 °C for 60 min in air. After cooling to 100 °C, the films were immersed in a 0.3 mM of MK-2 solution for 24 h. The resulting electrodes were rinsed with acetonitrile. After drying at room temperature, the porous electrode was covered by a Pt vapor deposition.

Results and discussion

3.1. Current profile of DSCs based on ionic liquid

Typical current-voltage (J–V) curves of DSCs based on ionic liquid are shown in figure 2. The voltage is scanned from −0.1 V to 0.8 V at scan rate of about 185 mV s−1. The concentration of I3− in the electrolyte is 0.05 M (---), 0.1 M (--), 0.15 M (----), and 0.26 M (-----).

The time course of the photocurrent density (Jsc) at short circuit is shown in figure 3 and is measured under 650 nm laser illumination. The time-course of photocurrent of DSCs at the concentration of 0.03 M with various light intensities is shown in figure 3(a). The degree of the current decay was enhanced with increase of the light intensity. The current decreases in 5 s over 2.7 mW cm−2 of the light intensity. On the other hand, the current becomes constant against time below 2.7 mW cm−2 of the light intensity. The current decay is strongly related to the J–V curve in figure 2. During the sweep of voltage, the current decrease with time. Therefore, the strange J–V curve is observed. Time-course of current of DSCs at 25.9 mW cm−2 of 650 nm laser with various concentrations of I3− is also shown in figure 3(b). The decay of current against time is also observed. The current becomes constant against time with increase of the concentration of I3−.

The results are in good agreement with the relationship between the I–V curve and the concentration. These I–V curves became normal shape with increase of the concentration of I3− because current does not depend on the time.

In the measurement of figure 3(a), the orange color of I3− around counter electrode disappeared after each measurement over 2.7 mW cm−2. The phenomenon means that the concentration of I3− becomes 0.

The concentration of I− is 0.65 M and is larger than that of I3−. Therefore, the ion transport Γ can be neglected. The concentration of I3− around counter electrode decreases with increase of light intensity. The lack of the I3− around counter electrode induces the decay of current against time. The ion transport of I3− from TiO2 to the counter electrode influences on the time course of photocurrent when the concentration is 0 around the counter electrode. On the other hand, the lack of I3− can be suppressed by the high initial concentration of I3− as shown in figure 3(b). The ion transport limited current is...
induced by the strong light intensity or lower concentration of $I_3^-$. The detailed model is shown in section 3.2.

The relationship between current density at short circuit and light intensity is shown in figure 4. The $J_{sc}$ linearly increases with increase of the light intensity at high concentration of $I_3^-$. The $J_{sc}$ is constant against time. The $J_{sc}$ at 0 s is also linearly related to the light intensity. However, the $J_{sc}$ at 30 s is saturated over a light intensity at lower concentration. The current decays against time at lower concentration. The light intensity in photon flux corresponds to the amount of photons per time. The slow ion transport rate cannot cover the incident speed of photons. The saturated $J_{sc}$ as shown figure 4 corresponds to the value at 30 s from 9.8 mW cm$^{-2}$ to 25.9 in figure 3(a). The consistency shows the saturated $J_{sc}$ is due to the ion transport in these DSCs.

3.2. Charge transport in DSCs

3.2.1. Model of charge transport. The schematic structure of DSCs is shown in figure 1. The $J_{g}$ is expressed as the photogenerated electron flux in TiO$_2$ including charge injection from dye to TiO$_2$, electron transfer from $I^-$ to oxide dye, the electron diffusion in TiO$_2$. The $J_{dif}$ is expressed as the diffusion limited current including transports of $\Gamma$ and $I_3^-$. The reaction rate at counter electrode also influences $J_{dif}$. However, the rate can be neglected because it is faster than ion transports. The thicknesses of spacer for DSCs and the TiO$_2$ film are defined as $T$ and $d$, respectively.

In the case of $J_{dif}>J_{g}$, the current in DSCs is explained by the diffusion equation of the electrons in TiO$_2$ as the following equation [16–20]

$$\frac{\partial n(x, t)}{\partial t} = D \frac{\partial^2 n(x, t)}{\partial x^2} - \frac{n(x, t)}{\tau} + \alpha I_0 e^{-\alpha x}. \quad (1)$$

The current of DSCs is dominated by $J_{g}$. The fast ion transports can compensate the ions for electron transfer at the interface. The $J_{sc}$ is generally linear related to the light intensity below 1 sun. The response of the $J_{sc}$ depends on the electron transport.

In the case of $J_{g}>J_{dif}$, the surface concentration of $\Gamma^-$ and $I_3^-$ at interface becomes 0 because the ion transport cannot compensate the ions for electron transfer at the interface. The current depends on the ion transports. The distribution of ions in DSCs has to be considered. Papageorgiou et al [6, 7] had investigated the relationship between the charge (electron, $\Gamma^-$ and $I_3^-$) transport in the electrolyte and the photovoltaic performance by the ion transport model. The ion transport model [6, 7, 9] was modified by the followings to explain $J_{sc}$ against physical parameters in DSCs and determined the suitable physical parameters for favorable ion transport in ionic liquid. (i) The light absorption profile is introduced into the ion diffusion equation. (ii) The diffusion coefficient ($D_{OX}$) in porous TiO$_2$ is different from that ($D_{OX}^b$) in bulk electrolyte solution. The $D_{OX}^b$ can be expressed by $\beta D_{OX}$. The $\beta$ value of $D_{OX}^b$ in the electrolyte of MPImI was 5 when the diffusion limited currents of TiO$_2$ sandwiched by Pt electrode were measured. (iii) The current is influenced by the distribution of the concentration of $I_3^-$ since the concentration of $\Gamma^-$ is ten times larger than that of $I_3^-$. (iv) The decrease of $I_3^-$ due to charge recombination in porous TiO$_2$ can be neglected. (v) the concentration of $I_3^-$ at $T$ needs to be 0 or over.
In porous TiO₂ (0 ≤ x ≤ d), the concentration of I₃⁻ (C₀ₓ) can be expressed by
\[
\frac{dC_{OX}}{dt} = D_{OX} \frac{d^2C_{OX}}{dx^2} + \frac{a \phi I_0}{2 \rho} e^{-a x},
\]
(2)
where x is distance from TCO, t is time, ρ is porosity of porous TiO₂, I₀ is the incident photon flux corrected for reflection loss, ϕ is the electron transfer and transport yield, and α is the absorption coefficient. In the bulk electrolyte solution layer of DSCs (d ≤ x ≤ T), the concentration (C₀ₓ) of I₃⁻ can be expressed by
\[
\frac{dC_{OX}}{dt} = D_{OX} \frac{d^2C_{OX}}{dx^2}.
\]
(3)

The flux (Jₘₐₓ) of ion transport can be expressed by the followings. The flux (J₉₆) in porous TiO₂ (0 ≤ x ≤ d) is
\[
J_{TIO₂} = \rho D_{OX} \frac{dC_{OX}}{dx}.
\]
(4)
The flux (Jₖ₆) in the bulk electrolyte solution (d ≤ x ≤ T) is
\[
J_{flux} = D_{OX} \frac{dC_{OX}}{dx}.
\]
(5)
The concentration gradient of Cₓ at TCO equals 0 as the boundary condition at x = 0
\[
\left( \frac{dC_{OX}}{dx} \right)_{x=0} = 0.
\]
(6)
I assumed that two boundary condition can be fixed at x = d. Because the electrolyte solution is continuous at x = d, the Cₓ value calculated from equation (2) must equal to that from equation (3) at x = d
\[
C_{OX}(x = d, 0 ≤ x ≤ d) = C_{OX}(x = d, d ≤ x ≤ T).
\]
(7)
The flux of equation (4) must be same as that of equation (5) at x = d
\[
\rho D_{OX} \left( \frac{dC_{OX}}{dx} \right)_{x=d} = D_{OX} \left( \frac{dC_{OX}}{dx} \right)_{x=d}.
\]
(8)
The total amount of I₃⁻ has to be conserved in DSCs
\[
\int_{x=0}^{x=d} \rho C_{OX}(x)dx + \int_{x=d}^{x=T} C_{OX}(x)dx = C_{OX}^0 \left( \rho d + T - d \right).
\]
(9)
In steady state, the left side of equations (2) and (3) equals 0. The distribution of Cₓ can be solved from equations (2)–(9). The Cₓ is expressed as follows
\[
C_{OX}(x) = -\frac{\phi I_0}{2 \rho D_{OX}} \left( x + \frac{1}{\alpha} \left( e^{-a x} - 1 \right) \right) + C_{OX}(0)
\]
(10)
at 0 ≤ x ≤ d, and
\[
C_{OX}(x) = \frac{\phi I_0}{2 D_{OX}} \left( e^{-a d} - 1 \right) (x - d) - \frac{\phi I_0}{2 \rho D_{OX}} \left( d + \frac{1}{\alpha} (e^{-a d} - 1) \right) + C_{OX}(0)
\]
(11)
at d ≤ x ≤ T.

When C₀ₓ is defined as the initial concentration of I₃⁻, Cₓ(0) can be expressed by the following equation
\[
C_{OX}(0) = C_{OX}^0 + \phi I_0 \frac{1}{D_{OX}} \left\{ d \left[ \frac{1}{2} - \frac{1}{\alpha} \right] - \frac{1}{\alpha^2} \left[ e^{-a d} - 1 \right] \right\} - \frac{1}{\rho D_{OX}} \left( e^{-a d} - 1 \right) \left( T - d \right) + \frac{1}{D_{OX}} \left[ e^{-a d} - 1 \right] \left( T - d \right)
\]
(12)
The concentration distribution (Cₓ(0)) from TCO to the counter electrode at various light intensity is shown in figure 5(a). The T is 30 μm, d is 13 μm, ϕ is 0.65, Cₓ(0) is 0.03 M, Dₓ is 3.5 × 10⁻⁷ cm² s⁻¹, β is 5, α at 650 nm is 1200 cm⁻¹, respectively. As the light intensity increases, the Cₓ(0) increases and Cₓ(T) decreases.

The linear relationship between photocurrent and light intensity can be explained by equation (13).
\[
J_{SC} = -nFJ_{flux} = -2FD_{OX} \left( \frac{dC_{OX}}{dx} \right)_{x=T}
\]
(13)
where n is electrons per this reaction and F is Faraday constant, respectively.

The linear relationship between photocurrent and light intensity can be explained by equation (13).

Cₓ(T) becomes minus at light intensity of 3.1 mW cm⁻² as shown in figure 5(a). In a real device, Cₓ(T) of equation (11) has to be 0 or over as described as (v). The model needs to be modified to explain the ion transport limitation. When Cₓ(T) is calculated to be under 0, the Cₓ(T) must keep being 0, and equation (8) is neglected. This assumption means that (dCₓ/dx)ₓ=T becomes constant against I₀. Jₓ is dominated by the diffusion of I₃⁻ and becomes constant against I₀ defined as diffusion limited current (Jₓ). The constant Jₓ is due to (dCₓ/dx)ₓ=T of equation (13). The relationship between the calculated Jₓ and the light intensity (I₀) is shown in figure 5(b). The calculated Jₓ from figure 5(b) was 1.3 mA cm⁻², corresponding to the experimental results in figures 3(a) and 4.

3.2.2. Saturated photocurrent versus diffusion coefficient of I₃⁻ or initial concentration. Jₓ has to be over 30 mA cm⁻² which is calculated from the external quantum efficiency (EQE) of 95% from 400 nm to 900 nm in solar light. Otherwise, the solar to energy conversion efficiency of DSCs is limited by
becomes minus at intensity at the same condition of (a). The black circle is due to this model. The value calculated from equation (13) when \( C_{\text{OX}}(T) \) becomes 0. The white circle is the value calculated from equation (13) when \( C_{\text{OX}}(T) < 0 \) is permitted in this model.

Figure 5. (a) The calculated concentration distribution \( C_{\text{OX}}(x) \) of \( \Gamma^- \) in a DSC at the concentration of 0.05 M with the light intensity of 2.8 mW cm\(^{-2} \) (---), 3.7 mW cm\(^{-2} \) (---), 4.6 mW cm\(^{-2} \) (---) and 5.5 mW cm\(^{-2} \) (--). The red solid line is the \( C_{\text{OX}}(x) \) at 9.2 mW cm\(^{-2} \) and becomes minus at \( x \approx 30 \mu \text{m} \). The right side is TCO, and the left side is the counter electrode. The \( T \) is 30 \( \mu \text{m} \), \( d \) is 13 \( \mu \text{m} \), \( \phi \) is 0.65, \( C_{\text{OX}}^0 \) is 0.05 M, \( D_{\text{OX}}^b \) is 3.5 \times 10^{-7} \text{ cm}^2 \text{s}^{-1}, \( \beta \) is 5, \( \alpha \) at 650 nm is 1200 cm\(^{-2} \), respectively. (b) The relationship between calculated \( J_{\text{sc}} \) and the light intensity at the same condition of (a). The black circle is due to this model. The \( J_{\text{sc}} \) is constant when \( C_{\text{OX}}(T) \) becomes 0. The white circle is the value calculated in equation (13) when \( C_{\text{OX}}(T) < 0 \) is permitted in this model.

Figure 6. (a) The calculated saturated current density \( J_{\text{sc}}' \) versus the diffusion coefficient \( D_{\text{OX}}^b \) at the initial concentration \( C_{\text{OX}}^0 \) of 0.05 M ( ), 0.1 M (△), 0.15 M (■), 0.2 M (○), and 0.25 M (◆). (b) The plot of calculated \( J_{\text{sc}}' \) versus \( C_{\text{OX}}^0 \) at the \( D_{\text{OX}}^b \) of 5 \times 10^{-6} ( ), 2 \times 10^{-6} (△), 1.5 \times 10^{-6} ( ), 1 \times 10^{-6} (△), 5 \times 10^{-7} (■), 3.5 \times 10^{-7} (○), and 1 \times 10^{-7} \text{ cm}^2 \text{s}^{-1} (◆). The other parameters of these calculations are same as figure 5.

the ion transport. The diffusion limited current density \( (J_{\text{diff}}) \) can be generally expressed by the following formula [15]

\[
J_{\text{diff}} = \frac{2nFDC}{d} \tag{14}
\]

\( J_{\text{diff}} \) depends on the diffusion coefficient of ions \( (D) \), carrier density \( (C) \), and the distance \( (d) \) of the ion transport, which respectively corresponds to the diffusion coefficient \( (D_{\text{OX}}^b) \) of \( \Gamma^- \), the \( \Gamma^- \) value of \( \Gamma^- \), and the \( d \) value of the TiO\(_2\) film. Therefore, each parameter needs to be discussed to improve \( J_{\text{sc}}' \).

The relationship between the calculated \( J_{\text{sc}}' \) and \( D_{\text{OX}}^b \) or \( C_{\text{OX}}^0 \) is shown in figure 6. \( J_{\text{sc}}' \) increases with increase of \( D_{\text{OX}}^b \) as shown in figure 6(a). The relationship between \( J_{\text{sc}}' \) and \( C_{\text{OX}}^0 \) is related to the \( C_{\text{OX}}^0 \). The \( J_{\text{sc}}' \) also increases with increase of \( C_{\text{OX}}^0 \) as shown in figure 6(b). In case of \( C_{\text{OX}}^0 = 0.05 \text{ M} \), the \( D_{\text{OX}}^b \) needs to be over \( 1 \times 10^{-5} \text{ cm}^2 \text{s}^{-1} \). The typical \( C_{\text{OX}}^0 \) value is 0.05 M in the electrolyte solution based on acetonitrile. The \( D_{\text{OX}}^b \) value of this electrolyte solution is about \( 1 \times 10^{-4} \text{ cm}^2 \text{s}^{-1} \). Therefore, the electrolyte solution based on acetonitrile can fully compensate the photon flux of the solar light. On the other hand, the \( D_{\text{OX}}^b \) based on a typical ionic liquid is \( 5 \times 10^{-7} \text{ cm}^2 \text{s}^{-1} \), about 100 times smaller than that of the electrolyte solution based on acetonitrile. \( J_{\text{sc}}' \) becomes about 1% of the electrolyte solution based on acetonitrile.

The electrolyte solution with large \( C_{\text{OX}}^0 \) value needs to be prepared to improve \( J_{\text{sc}}' \). In the case of MPImI, the \( C_{\text{OX}}^0 \) value has to be over 0.26 M. However, the \( I_3^- \) cannot be dissolved over 0.26 M in this electrolyte. And the strong light absorption of \( I_3^- \) reduces the light harvesting efficiency of the dye on TiO\(_2\) in DSCs. The way to increase \( C_{\text{OX}}^0 \) is limited by the solubility and the light absorption of \( I_3^- \).
Molecular design has been used to try to decrease the viscosity of an ionic liquid [3, 5] because $D_{b_{\text{OX}}}$ increases with decrease of viscosity. A suitable $D_{b_{\text{OX}}}$ value for DSCs needed to be shown for the design of the ionic liquid. $D_{b_{\text{OX}}}$ needs to be over $1.5 \times 10^{-7} \text{cm}^2 \text{s}^{-1}$ from figure 6(b) and the $C_{b_{\text{OX}}}$ needs to be over 0.1 M to certainly enhance $J_{sc}$. The high solubility (>0.3 M) and low visible absorption properties of a redox mediator also need to be designed for DSCs.

3.2.3. Saturated photocurrent influenced by meso-porous layer of TiO$_2$ The effect of porous TiO$_2$ on the ion transport also needs to be discussed to improve $J_{sc}$. The plots of calculated $J_{sc}$ versus $D_{b_{\text{OX}}}$ or $C_{b_{\text{OX}}}$ again are shown in figure 7 to compare with each diffusion limited current density ($J_{\text{diff}}$) of the porous TiO$_2$ film and the bulk electrolyte in the DSC. The solid line in figure 7(a) is due to $J_{\text{diff}}$ of the porous TiO$_2$ layer and is calculated from equation (14) at $C=C_{b_{\text{OX}}}=0.05 \text{M}$, $d=13 \mu\text{m}$, and $D=D_{b_{\text{OX}}}$, respectively. The dashed line is due to $J_{\text{diff}}$ of the bulk electrolyte and is calculated from equation (14) at $C=C_{b_{\text{OX}}}=0.05 \text{M}$, $d=17 \mu\text{m}$, and $D=D_{b_{\text{OX}}}$, respectively. The slope of $J_{sc}$ versus $D_{b_{\text{OX}}}$ is similar to that of $J_{\text{diff}}$ versus $D_{b_{\text{OX}}}$ of the porous TiO$_2$ layer. The solid line in figure 7(b) is due to $J_{\text{diff}}$ of the porous TiO$_2$ layer and is calculated from equation (14) at $C=C_{b_{\text{OX}}}=0.05 \text{M}$, $d=13 \mu\text{m}$, and $D=D_{b_{\text{OX}}}=7 \times 10^{-8} \text{cm}^2 \text{s}^{-1}$, respectively. The dashed line is due to $J_{\text{diff}}$ of the bulk electrolyte and is calculated from equation (14) at $C=C_{b_{\text{OX}}}=0.05 \text{M}$, $d=17 \mu\text{m}$, and $D=D_{b_{\text{OX}}}=3.5 \times 10^{-7} \text{cm}^2 \text{s}^{-1}$, respectively. The slope of $J_{sc}$ versus $C_{b_{\text{OX}}}$ is also similar to that of $J_{\text{diff}}$ versus $C_{b_{\text{OX}}}$ of the porous TiO$_2$ layer. The results show that the ion transports in the porous TiO$_2$ layer influence the total ion transport in DSCs.

The $\beta$ is defined as $D_{b_{\text{OX}}}/D_{\text{OX}}$. The $D_{\text{OX}}$ is usually smaller than $D_{b_{\text{OX}}} (\beta>1)$. The mechanism of $\beta>1$ is under investigation. The $\beta$ value seems to depend on the viscosity. The ions can move more randomly when the viscosity is low. Ions easily collide with the surface of porous structure. Therefore, the diffusion rate of ions slows down in porous TiO$_2$. On the other hand, the $\beta$ value seems to decrease with increase of viscosity of the electrolyte. In the case of high viscosity, ions cannot quickly move in the electrolyte solution. The probability of the collision between ions and the surface of porous structure must become smaller.

The relationship between the calculated $J_{sc}$ and thickness ($d$) of TiO$_2$ is shown in figure 8. The results can be explained by using equation (14). The ion can be easily supplied with decrease of the distance. $J_{sc}$ is exponentially influenced by the $d$ value. The thin TiO$_2$ films are favorable for the ion transport, especially in the case of small $D_{b_{\text{OX}}}$. However, the light harvesting efficiency of dye on TiO$_2$ decreases with decrease of $d$. The high light absorption ability of dyes needs to be designed for DSCS based on ionic liquid. In the case of $C_{b_{\text{OX}}}=0.05 \text{M}$, $D_{b_{\text{OX}}}$ needs to be $5 \times 10^{-5} \text{cm}^2 \text{s}^{-1}$, corresponding to the condition of figure 6(a).
4. Conclusion

The effect of $\text{I}_3^-$ transport in the liquid electrolyte on the photovoltaic properties of dye-sensitized solar cells (DSCs) was investigated by the ion transport model and experimental results. The $J_{sc}$ becomes constant against light intensity when the concentration ($C_{\text{OX}(T)}$) of $\text{I}_3^-$ at the counter electrode becomes 0. The saturated $J_{sc}$ is named as the saturated current ($J_{sc}^s$) and depends on the ion transport in the electrolyte solution of DSCs. The $J_{sc}^s$ value has to be over 30 mA cm$^{-2}$ which is calculated from EQE of 95% from 400 nm to 900 nm in solar light. The $J_{sc}^s$ value can be determined by the thickness ($d$) of the TiO$_2$ layer, the initial concentration ($C_{\text{OX}0}$) and the diffusion coefficient ($D_{\text{OX}b}$) of $\text{I}_3^-$. The $J_{sc}^s$ value can increase with increase of $C_{\text{OX}0}$ and $D_{\text{OX}b}$ and with decrease of $d$.

In the case of $C_{\text{OX}0} = 0.05$ M, $D_{\text{OX}b}$ needs to be $5 \times 10^{-5}$ cm$^2$ s$^{-1}$. Otherwise, the $d$ value has to be below 10 $\mu$m. The $J_{sc}^s$ value can increase with increase of the $C_{\text{OX}0}$ value. Because $\text{I}_2$ cannot dissolve over 0.26 M in the ionic liquid, the $D_{\text{OX}b}$ needs to be over $1.5 \times 10^{-6}$ cm$^2$ s$^{-1}$ to keep over 30 mA cm$^{-2}$ of $J_{sc}^s$.

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