

Synthesis of Low-Viscosity Ionic Liquids for Application in Dye-Sensitized Solar Cells

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Abstract: Two types of ionic liquids (ILs), 1-(3-hexenyl)-3methyl imidazolium iodide and 1-(3-butenyl)-3-methyl imidazolium iodide, are synthesized by introducing an unsaturated bond into the side alkyl chain of the imidazolium cation. These new ionic liquids exhibit high thermal stability and low viscosity (104 cP and 80 cP, respectively). The molecular dynamics simulation shows that the double bond introduced in the alkane chain greatly changes the molecular system space arrangement and diminishes the packing effi-

Introduction

Because of their simplicity and high flexibility, dye-sensitized solar cells (DSSCs) have attracted much attention.^[1] Room temperature ionic liquids (ILs) are perceived to be an attractive candidate as a new class of electrolytes,^[2] possessing various advantages such as high thermal stability and ionic conductivity. In particular, imidazolium salt-based ILs have been widely

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- Supporting information and the ORCID identification number(s) for the au-
- https://doi.org/10.1002/asia.201901130.

Chem. Asian J. **2019**, 00, 0–0

ciency, leading to low viscosity. The low viscosity of the synthesized ionic liquids would enhance the diffusion of redox couples. This enhancement is detected by fabricating dyesensitized solar cells (DSSCs) with electrolytes containing the two ILs and I₂. The highest efficiency of DSSCs is 6.85% for 1-(3-hexenyl)-3-methyl imidazolium iodide and 5.93% for 1-(3-butenyl)-3-methyl imidazolium iodide electrolyte, which is much higher than that of 5.17% with the counterpart 1-hexyl-3-methyl imidazolium iodide electrolyte.

investigated as electrolytes for DSSCs.^[3] However, pure imidazolium iodide-based ILs have high viscosity and obstruct the diffusion of the redox couple, limiting the improvement of the device performance.^[4] To decrease the viscosity of IL electrolytes, numerous efforts have been made through mixing the imidazolium iodide ILs with volatile solvents or low-viscosity ILs.^[5] The addition of organic solvents into ILs has an inherent drawback due to the volatility of organic solvents.^[6] The introduction of relatively low-viscosity ILs with anions such as tetracyanoborate, tricyanomethanide and thiocyanate seems to be promising for high-performance DSSCs.^[4,5] However, the application of these low-viscosity ILs in DSSCs may be limited by their potential instability, toxicological and high costs. Hence, the development of imidazolium iodide-based ILs possessing low-viscosity is necessary for the enhanced performance of DSSCs.

The viscosity of ILs is determined by the interplay of coulombic and van der Waals interactions as well as hydrogen bond formation.^[7] Decreasing the alkyl chain length of the imidazolium cation reduces the van der Waals interaction between imidazolium cations, but the electrostatic attraction between cations and anions increases. Consequently, ILs with a medium chain length of $3 \approx 6$ carbon atoms, such as 1-hexyl-3methylimidazolium iodide (HMII), 1-propyl-3-methylimidazolium iodide (PMII) and 1-butyl-3-methylimidazolium iodide (BMII), have relatively low viscosity, mirroring the behavior of their conductivity, which is relatively high. Because of the lowviscosity property, PMII, HMII and BMII have been proven to a better candidate of choice for IL electrolytes, and they have achieved higher efficiency in DSSCs.^[8] It is believed that if the viscosity of the iodide melts could be further reduced, the mass transport and efficiency would be further improved. In nature, we know that the fluidity of liquid oil with unsaturated bonds is much more increased than that of fat with side-chain saturation. The packing efficiency of the oil is diminished by

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the presence of the unsaturated structure. Learning from that, we are encouraged to incorporate the unsaturated bond into high performance HMII and BMII (1-allyl-3-methylimidazolium iodide with an unsaturated bond from PMII is solid at ambient temperature), which are hypothesized to have a lower viscosity than their counterparts with a saturated structure.

Therefore, we synthesized two types of new ILs, 1-(3-hexenyl)-3-methyl imidazolium iodide (HeMII) and 1-(3-butenyl)-3methyl imidazolium iodide (BeMII) with an unsaturated bond and introduced into DSSCs for the first time. These two new ILs possess a lower viscosity (104 cP and 80 cP, respectively, at 27 °C) than their counterparts with saturated structures HMII (490 cP) and BMII (400 cP). The low viscosity of the two ILs could result in the enhanced diffusion of redox couples. Considering these results, we fabricated DSSCs using the two synthesized ILs separately to assess the potential advantages of low-viscosity ILs. Using electrolytes with one component IL, DSSCs with HeMII (BeMII) exhibit higher efficiency up to 6.85% (5.93%) at 1 sunlight (100 mW cm⁻²), which is higher than that of 5.17% with the counterpart HMII electrolyte. To our best knowledge, the efficiency of 6.85% is one of the best results for DSSCs with one component ionic liquid electrolyte. Many strategies, such as mixture of ILs, dye match and so on, are needed to further improve the efficiency of DSSC based on the low-viscosity ionic liquids.

Results and Discussion

Characterization of HeMII and BeMII

To compare the new ILs with the traditional ILs, we measured the viscosity of the two new ILs (HeMII, BeMII) and their counterparts with a saturated structure (HMII and BMII). The inherent viscosity of purified HeMII and BeMII was 104 cP and 80 cP, respectively, at 27 °C, which is much lower than that of their counterparts (490 cP for HMII and 400 cP for BMII). This result proves the feasibility of our design approach by incorporating the unsaturated bond to achieve low-viscosity ILs.

The thermal stability of the synthesized HeMII and BeMII was detected through TGA (Figure 1 a). Decomposition of the two ILs occurs above 230 °C, which indicates that the synthesized ILs with an unsaturated structure are thermally stable and could be a promising candidate electrolyte for practical DSSCs.

Molecular dynamics simulation methodology

The molecular dynamics simulation (MDS) calculation of HMII and HeMII was performed by applying the LAMMPS package for investigating the effect of double bonds in alkane chains on the system space arrangement. Snapshots of the MD simulation boxes and the radial distribution curves for HMII and HeMII are shown in Figure 2a–d. The packing density of HMII and HeMII calculated from the simulation boxes (Figure 2a,b) is 0.1966 and 0.1856 atom per Å, respectively. The MDS calculation in Figure 2c further reveals that the flexible HMII has a tight and regular system space arrangement with a peak at





Figure 1. (a) TGA curves of the two ILs, (b) J-V curves of DSSCs based on HeMII electrolytes with different I₂ contents, and (c) the relationship between J_{sc} and the radiant power for DSSCs using an electrolyte containing HeMII and I₂ with a molar ratio of 20:1.



Figure 2. (a) Snapshots of MD simulation boxes for HMII, (b) snapshots of MD simulation boxes for HeMII, (c) radial distribution curve of HMII, and (d) radial distribution curve of HeMII.

2.8 Å. Nevertheless, HeMII with a rigid double bond shows a loose system space arrangement with a peak at 4.6 Å, which is unstable in the system (Figure 2 d). The MDS calculation suggests that the double bond introduced in the alkane chain greatly changes the molecular system space arrangement and diminishes the packing efficiency of HeMII, which is closely correlated with the viscosity of ionic liquids.

The performance of DSSCs with different I₂ contents

The performance of the low-viscosity ILs was first investigated by adding different contents of iodine. In this part, we chose compound HeMII for the systematic investigation. The J-V curves of the champion DSSCs based on HeMII with different iodine contents are shown in Figure 1 b. The J-V curves and

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the corresponding photovoltaic parameters (short circuit current density (J_{sc}) , open circuit voltage (V_{oc}) , fill factor (FF) and energy conversion efficiency (η) for the individual device under different conditions are given in Figure S1, S2 and Table S1. The photovoltaic performances of these DSSCs were observed to deteriorate because of the simultaneous decrease in J_{sc} and $V_{\rm oc}$ when increasing the I₂ concentration. The efficiency declined from 3.27% to 1.76% with the decreasing molar ration of HeMII and I₂ from 20:1 to 7:1. The best efficiency is achieved by adding a small quantity of I₂ in HeMII. The optimal content of I₂ in the HeMII electrolyte is much lower than in the reference report (the molar ration of IL to I₂ is usually 10:1).^[9] Because the traditional imidazolium iodide ILs have a relatively high viscosity, enough iodine is added to guarantee that the triiodide could be transferred to the counter electrode by diffusion and a Grotthus-type, non-diffusional hopping mechanism.^[10] Our photoelectric results indicate that adding a small quantity of iodine in HeMII could assure the efficient diffusion of triiodide to the counter electrode because of the higher fluidity of HeMII, which is benefit to the mass transport. This can be proved by the power-law experiment, which refers to the relationship between J_{sc} and the radiant power. In Figure 1 c, it can be observed that the J_{sc} values show a nearly linear response to the radiant power, which means that the J_{sc} is not limited by the mass transport.^[11] Moreover, increasing the concentration of I_2 mainly enhances recombination and brings serious visible light absorption by I_3^- , leading to the worsening of $V_{\rm oc}$ and $J_{\rm sc}$, respectively.^[12] By lowering the viscosity of IL, a small quantity of I₂ in the HeMII electrolyte could simultaneously guarantee the effective diffusion of redox couples and delay the recombination reaction, which makes the low-viscosity HeMII potential for application in DSSCs because of the decreased corrosion of iodine to electrodes.

The effect of the Lil concentration on the performance of DSSCs

Figure 3a shows the J-V curve of the champion DSSCs using electrolytes with different contents of Lil. The J-V curves and the corresponding photovoltaic parameters for the individual device under different conditions are given in Figure S3, S4, and Table S2. It can be seen that the performance of the DSSCs was improved when Lil was added by increasing J_{sc}. For the electrolyte HeMII containing only I₂ and LiI, the DSSCs achieved an optimal efficiency of 4.47%, which is higher than that based on HMII (3.43%).

To explain the enhancement of J_{sc} , the D_{app} of I_3^- was estimated from the limiting current (J_{lim}) of the linear sweep voltammogramsaccording to the literature.^[13] The diffusion curves are presented in Figure 3b. The results of D_{app} are listed in Table 1. It can be observed that the variation trend of D_{app} of I_3^- agrees with that of J_{sc} when the molar ratio of Lil to HeMII is less than 3/20. To further explain the variation trend of J_{scr} the ionic conductivity (σ) was investigated. It can be observed that adding Lil in the electrolytes raises σ . Therefore, the improved Dapp of I_3^- and σ are responsible for the enhanced J_{sc} after adding Lil.





Figure 3. (a) J-V curves of the DSSCs based on electrolytes with different Lil content (20:1:0/1/3/5 represent the molar ratio of HeMII/I₂/LiI), (b) steadystate voltammogram curves of the electrolytes with Lil (20:1:0/1/3/5 represent the molar ratio of $HeMII/I_2/LiI$), (c) J-V curves of the DSSCs based on electrolytes with NMBI and GuNCS (20:0:0 represents the molar ratio of HeMII/NMBI/GuNCS: BeMII or HMII: electrolyte comprises of BeMII or HMII. I2, Lil, NMBI and GuNCS with a molar ratio of 20:1:3:4.5:4.5.), (d) dark current of the DSSCs based on electrolytes containing the two additives (the legend is molar ratio of HeMII/NMBI/GuNCS).

Table 1. The values of D_{app} and σ .									
HeMII/I ₂ /Lil	$J_{\rm lim} ({\rm I_3}^-)$	$D_{app} (I_3^-)$	J _{sc}	σ [mS cm ⁻¹]					
[molar ratio]	[mA cm ⁻²]	(10 ⁻⁶ cm ⁻² s ⁻¹)	[mA cm ⁻²]						
20:1:0	0.581	1.44	6.30	3.69					
20:1:1	0.754	1.86	8.89	4.04					
20:1:3	1.076	2.66	9.31	6.87					
20:1:5	0.734	1.81	9.14	5.39					

The effect of the additive content on the performance of DSSCs

To further improve the performance of DSSCs with the low-viscosity ILs, different amounts of two additives, guanidinium thiocyanate (GuNCS) and *N*-methylbenzimidazole (NMBI),^[14] were added to the electrolyte. The photovoltaic performance of the champion DSSCs assembled with additives is depicted in Figure 3 c and the corresponding detailed parameters are summarized in Table 2. The J-V curves and the corresponding photovoltaic parameters for the individual device under different conditions are given in Figure S5, S6 and Table S3. The performance of DSSCs is improved when the two additives are added by increasing J_{sc} and V_{oc} simultaneously. With the optimal concentration of the two additives, the cell based on the HeMII electrolyte approaches a maximum value of 6.85%, which exceeds the 5.17% efficiency of the HMII cell mainly contributing to the higher J_{sc} for the HeMII cell. Furthermore, the photovoltaic parameters (J_{scr} V_{ocr} FF and η) of the BeMIIbased cell with the optimal concentration of the two additives are 11.69 mA cm⁻², 675 mV, 0.752 and 5.93% respectively.

The enhancement in V_{oc} is attributed to two factors:^[13,14] the negative shift of the Fermi level of TiO₂ due to the negative

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Table 2. The champion photoelectric parameters of DSSCs with different additive contents.								
HeMII/NMBI/GuNCS [molar ratio]	J _{sc} [mA cm ⁻²]	V _{oc} [mV]	FF	η [%]				
20:0:0	9.31	645	0.744	4.47				
20:1.5:1.5	9.11	635	0.740	4.28				
20:3:3	12.53	685	0.731	6.27				
20:4.5:4.5	13.52	725	0.700	6.85				
20:6:6	10.04	715	0.730	5.24				
BeMII ^[a]	11.69	675	0.752	5.93				
HMII ^(b)	9.71	716	0.744	5.17				
[a] BeMII or [b] HMII: Electrolyte comprises of BeMII or HMII, I ₂ , LiI, NMBI								

surface charge buildup on the surface of TiO₂ through adding NMBI and the restraint of charge recombination in DSSCs due to the addition of NMBI and GuNCS which is clearly suggested by the dark current curves shown in Figure 3 d. An increase in J_{sc} is mainly related to the addition of GuNCS. As previously reported,^[14] the adsorbent guanidinium cation on the TiO₂ surface is beneficial for the electron injection.

To explore the effect of the additives on the interfacial charge transfer characteristics for DSSCs, electrochemical impedance spectroscopy (EIS) measurements are performed. The spectra shown in Figure 4a are measured under under 100 mW cm⁻² (AM 1.5) illumination in the open-circuit condition. The charge transfer resistance R_{ct2} at the TiO₂/dyes/electrolyte interface is obtained by fitting the impedance data employing the equivalent circuit shown in the inset of Figure 4a, where R_s is the equivalent series resistance and CPE represents the chemical capacitance. As Figure 4b shown, the R_{ct2} values are decreased with increasing the content of the two additives, indicating that the charge recombination is suppressed, while the electrons injection from dyes to the conduction band of TiO₂ is increased. This is attributed to the adsorbent guanidinium cation on the TiO₂ surface that favorable to increase electron injection from dyes to TiO₂.^[14b]



Figure 4. (a) Nyquist plots of EIS for DSSCs based on electrolytes with NMBI and GuNCS (20:0:0 represents the molar ratio of HeMII/NMBI/GuNCS) (the inset is the equivalent circuit), (b) R_{ct2} as a function of additive content in electrolyte.

Conclusion

Two novel ILs have been synthesized by introducing an unsaturated bond into the side alkyl chain of the imidazolium

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cation. These ILs possess a lower viscosity than their counterparts with saturated structures. The MDS shows that the double bond introduced in the alkane chain greatly changes the molecular system space arrangement. The TGA results indicate that the synthesized ILs with an unsaturated structure are thermally stable. Due to the low viscosity of the synthesized ILs, a small quantity of I₂ in the electrolyte could simultaneously guarantee the effective diffusion of redox couples and retard the recombination reaction, which gives them potential for application in DSSCs because of the decreased corrosion of iodine to electrodes. By optimizing the concentration of I2, Lil and the two additives, DSSCs using electrolytes with a single component IL HeMII (BeMII) exhibit an efficiency of 6.85% (5.93%), which is higher than that of 5.17% with the HMII electrolyte. This research may provide a novel perspective for designing low-viscosity ILs for DSSCs and other devices.

Experimental Section

Materials and reagents

Guanidinium thiocyanate (GuNCS) and iodine (I₂) were purchased from Acros. *N*-methylbenzoimidazole (NMBI), *p*-toluenesulfonyl chloride, 3-buten-ol and 3-hexen-l-ol were obtained from Alfa. HMII and BMII were prepared according to the literature.^[15] FTO glass (fluorine-doped tin oxide over-layer, and sheet resistance $20 \,\Omega \,\mathrm{cm}^{-2}$, Hake New Energy Co., Ltd., Harbin) was cut into $1.5 \times$ 0.8 cm² sheets as a substrate for precipitating TiO₂ porous film.

Synthesis route to HeMII and BeMII

The synthesized procedures of HeMII and BeMII are shown in Scheme 1.





Scheme 1. Synthesis route for HeMII and BeMII.

Procedure for the tosylation of alcohols^[16]

Pyridine (5 mL) and *p*-toluenesulfonyl chloride (8.38 g, 44.2 mmol) were added into 3-a butenol (2.94 g, 40.8 mmol) solution of CH_2CI_2 (100 mL) at 0 °C. The reaction was processed at room temperature for 24 h. At the end of the processing time, 5% aqueous HCl (100 mL) was added and the mixture was extracted with CH_2CI_2 three times; then, the combined organic layers were dried over anhydrous MgSO₄ and evaporated. Flash chromatography of the crude product of 3-butenyl-1-tosylate was performed (yield 87%).

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¹H NMR (400 MHz, CDCl3): $\delta =$ 7.78 (2 H, d), 7.34 (2 H, d), 5.60–5.74 (1H, m), 5.04-5.11 (2H, m), 4.03-4.08 (2H, t), 2.44 (s, 3H), 2.35-2.41 ppm (2 H, m).

(E)-3-Hexenyl-l-tosylate (yield 90%): obtained from (E)-3-hexen-l-ol; colorless oil: ¹H NMR (400 MHz, CDC1₃) $\delta = 7.78$ (2 H, d), 7.33 (2 H, d), 5.46-5.50 (1H, m), 5.17-5.20 (1H, m), 4.00-4.02 (2H, t), 2.45 (3H, s), 2.35-2.43 (2H, m), 1.95-2.01 (2H, m), 0.90-0.95 ppm (3H, t).

Procedure for the formation of the iodides

Nal was added into an acetone solution of 3-butenyl-1-tosylate. The mixture was heated at reflux overnight, cooled, evaporated, added to water and extracted with CH_2CI_2 three times; then, the organic layers were dried over anhydrous MgSO₄ and evaporated. Flash chromatography of the crude product of 4-iodo-1-butene as a yellow oil yielded the following (yield 85%): ¹H NMR (400 MHz, CDC1₃) δ = 5.83–5.70 (1 H, m), 5.12–5.08 (2 H, m), 3.21–3.17 (2 H, t), 2.58-2.66 ppm (2 H, m).

(E)-l-lodo-3-hexene (yield 85%): obtained from (E)-3-hexenyl-l-tosylate: $\delta = 5.50-5.56$ (1 H, m), 5.27–5.33 (1 H, m), 3.12–3.16 (2 H, t), 2.60-2.67 (2H, m), 2.00-2.07 (2H, m), 0.96-1.01 ppm (3H, t).

Synthesis of HeMII and BeMII

Briefly, 4-iodo-1-butene or l-iodo-3-hexen (0.3 mol) was added into the freshly distilled N-methylimidazole (0.25 mol) under Ar to avoid the oxidation of iodide. After that, the mixture was refluxed for 12 h under Ar. The crude compound was dissolved in water and extracted with CH₂Cl₂ at least three times to remove unreacted iodide. After removing water by the rotary evaporator, the resulting liquid was dried in a vacuum at 100 °C for 48 h.

BeMII (yield 50%):1H NMR (300 MHz, CDCl₂): $\delta = 10.18$ (s, 1 H), 7.38 (s, 2H), 5.80 (dt, J=17.1, 8.6 Hz, 1H), 5.19–5.03 (m, 2H), 4.45 (t, J= 6.8 Hz, 2 H), 4.10 (s, 3 H), 2.70 ppm (q, J=6.8 Hz, 2 H) (Figure S7). MS (ESI-MS): positive ion: $m/z = 137.1 [C_8 H_{13} N_2]^+$, calculated 137.2; negative ion: m/z = 127 [I]⁻, calculated 126.9. FTIR spectra for BeMII is shown in Figure S8.

HeMII (yield 95%): ¹H NMR (300 MHz, CDCl3): $\delta = 10.09$ (s, 1 H), 7.42 (d, J=11.1 Hz, 2 H), 5.44 (q, J=17.7, 7.9 Hz, 2 H), 4.38 (t, J=6.6 Hz, 2 H), 4.10 (s, 3 H), 2.67 (q, J = 6.3 Hz, 2 H), 2.02–1.82 (m, 2 H), 0.87 ppm (t, J = 7.5 Hz, 3 H) (Figure S9). MS (ESI-MS): positive ion: $m/z = 165.1 [C_{10}H_{17}N_2]^+$, calculated 165.2; negative ion: m/z = 127[I]⁻, calculated 126.9. FTIR spectra for HeMII is shown in Figure S10.

Assembling of DSSCs

The fabrication procedure for the TiO₂ electrode was described in our previous work.^[3a, 17] In detail, The TiO₂ nanocrystallinefilm consisted of a 2.6 μ M transparent TiO₂ layer (particle size of 20–30 nm) and a 3.8 μ M scattering layer (a mixture of 250 nm polystyrene spheres and 20–30 nm $\mathrm{TiO}_{\mathrm{2}}$ nanoparticles with a ratio of solid content of 1:10). After sintering, the films were immersed in a 0.5 mm N3 dye solution for 24 h. The platinum layered counter electrode was prepared by a sputtering method. DSSCs were assembled by injecting the IL electrolyte into the gap between the counter electrode and the dye sensitized TiO₂ electrode. The active area of the cell was 0.20 cm².

Details for molecular dynamics simulation methodology

Based on the molecular dynamics simulation of HMII and HeMII, the effect of double bonds in alkane chains on the system space arrangement was investigated. The molecular dynamics simulations methodology was performed by applying the LAMMPSpackage.^[18] The Van der Waals' force was calculated using the 12-6 Lennard-Jones famous potentials ULJ(rij) model with a cutoff distance of 12 Å. All calculations were performed under the periodical boundary condition in three dimensions. The models of bond, angle, dihedral, van der Waals and electrostatic interactions were prepared by using a classical molecular dynamic potential field^[19] to the following equation:

$$\begin{split} V(r) &= \sum_{\text{bonds}} k_{\text{b}} (r - r_0)^2 + \sum_{\text{angles}} k_{\theta} (\theta - \theta_0)^2 \\ &+ \sum_{\text{dihedrals}} k_{\chi} \left[1 + \cos(n_0 \chi - \delta_0) \right] \\ &+ \sum_{\text{impropers}} k_{\Psi} (\Psi - \Psi_0)^2 \\ &+ \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \left\{ 4 \varepsilon_{ij} \left[\left(\frac{\sigma_{ij}}{r_{ij}} \right)^{12} - \left(\frac{\sigma_{ij}}{r_{ij}} \right)^6 \right] + \frac{q_i q_j}{r_{ij}} \right\} \end{split}$$

All of the symbols shown in the equation represent their original meaning. All of the parameters used in this work are listed in the Table S4.^[20] The velocity-verlet algorithm was applied to integrate the equations of motion with a time step equal to 1 fs. First, the 70 ns NPT equilibration was conducted at 500 K. Moreover, the 200 ns NPT equilibration was also operated at 303.15 K to reach the equilibrium state.

Measurements and instruments

The measurements and instruments used in this work are presented in the Supporting Information. Photocurrent density-voltage (J-V) measurements were performed using a Keithly 2611 Source Meter (Keithley Instruments, Inc., USA) equipped with a solar simulator (Newport) simulating AM 1.5 sunlight at 100 mW cm⁻² irradiance. The ILs were characterized by 1H NMR (Bruker 400 M) and EIS-MS (BIFLEX III). Thermogravimetric analyzer (TGA) measurements were performed using DSC822e by METTLER Toledo Instruments. The apparent diffusion coefficient (D_{app}) of the triiodide was measured by using a Solartron SI 1287 electrochemical instrument, and the ionic conductivity was measured by using a Solartron SI 1287 electrochemical interface and a Solartron 1255B frequency response analyzer according to the literature.^[21] Briefly, to investigate D_{app} of I_3^- ions in electrolytes, symmetric Pt-Pt cells were assembled and characterized by means of the steady-state cyclic voltammetry at a scan rate 10 mV s^{-1} , and the voltage was swept from -0.6 to 0.6 V. Dapp of I_3^- was calculated from the steady-state current (J_{lim}) using the following equation:

$$D_{\rm app} = \frac{J_{\rm lim}d}{2n{\rm Fc}}$$

where n=2 is the electron number in the electrode reaction, F is the Faraday constant, and c is the bulk concentration of I_3^- ions, d is the thickness of electrolyte between two Pt electrodes. The σ was measured on a self-contained cell model with a sandwich configuration of stainless steel electrode/electrolyte/stainless steel electrode. The σ value was calculated from the measured bulk electrolyte resistance (R) on the basis of the following equation:

 $\sigma = L/RA$

where L is the thickness of the electrolyte, A is the contact area between the electrolyte and stainless steel electrode.

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Acknowledgements

This work was supported by the National Natural Science Foundation of China (51303186, 51673204, 21502195) and the National Materials Genome Project (2016YFB0700600).

Conflict of interest

The authors declare no conflict of interest.

Keywords: dye-sensitized solar cell \cdot electrolyte \cdot ionic liquid \cdot viscosity

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Manuscript received: August 13, 2019 Revised manuscript received: September 15, 2019 Accepted manuscript online: October 9, 2019 Version of record online:

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FULL PAPER

Two types of ionic liquids, HeMII and BeMII, with low viscosity are synthesized and the best efficiency of dye-sensitized solar cells (DSSCs) with these ionic liquids is 6.85% and 5.93%, respectively.



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Synthesis of Low-Viscosity Ionic Liquids for Application in Dye-Sensitized Solar Cells

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