

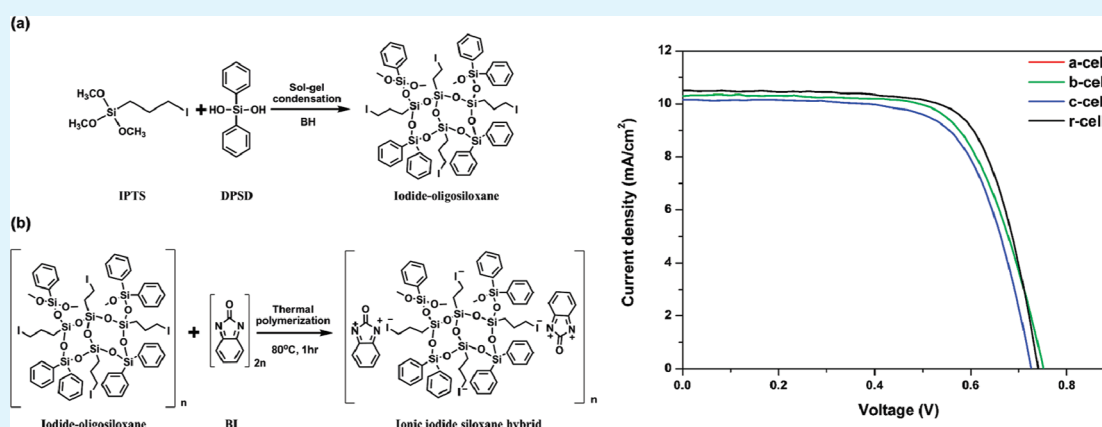
# Novel Ionic Iodide-Siloxane Hybrid Electrolyte for Dye-Sensitized Solar Cells

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## ABSTRACT:



A novel ionic siloxane hybrid electrolyte was fabricated by thermal polymerization of iodide-oligosiloxane resin. The nanosized iodide-oligosiloxane was synthesized by a simple sol–gel condensation of 3-iodopropyltrimethoxysilane and diphenylsilanediol. It is found that the composition and concentration of the oligosiloxane used in the electrolyte affect the performance of the dye-sensitized solar cells (DSSCs). An optimized DSSC with the hybrid electrolyte using smaller molecular-sized oligosiloxane with a greater amount of iodide groups presented solar to electricity conversion efficiency of 5.2% at 1 sunlight ( $100 \text{ mW cm}^{-2}$ ), which is comparable to that afforded by a liquid electrolyte.

**KEYWORDS:** dye-sensitized solar cell, gel electrolyte, alkoxy silane, sol–gel, organic–inorganic hybrid materials

## INTRODUCTION

Dye-sensitized solar cells (DSSCs) have attracted much attention because of their high solar to electricity conversion efficiency (i.e., >11% with liquid electrolyte at 1 sunlight, AM 1.5), low cost, and environmentally friendly properties.<sup>1</sup> Recently, DSSCs have also been used in building-integrated photovoltaics (BIPV) windows.<sup>2</sup> However, they employing liquid electrolytes may suffer from drawbacks such as the volatility of liquid state solvents and their permeation through sealants. Therefore, research on quasi-solid state polymers and hybrid electrolytes is being carried out for the preparation of hermetically sealed solid-state DSSCs that do not undergo the evaporation of liquids at high temperature.

P-type semiconductors, such as CuI and CuSCN,<sup>3</sup> conducting polymers,<sup>4</sup> and ionic liquids and gelled matrices,<sup>5,6</sup> are widely used for the solidification of liquid electrolytes. During the solidification process, cross-linked networks are formed and the molecules comprising the liquid electrolyte are trapped in cages.<sup>7,8</sup> However, for DSSCs incorporating these quasi-solid

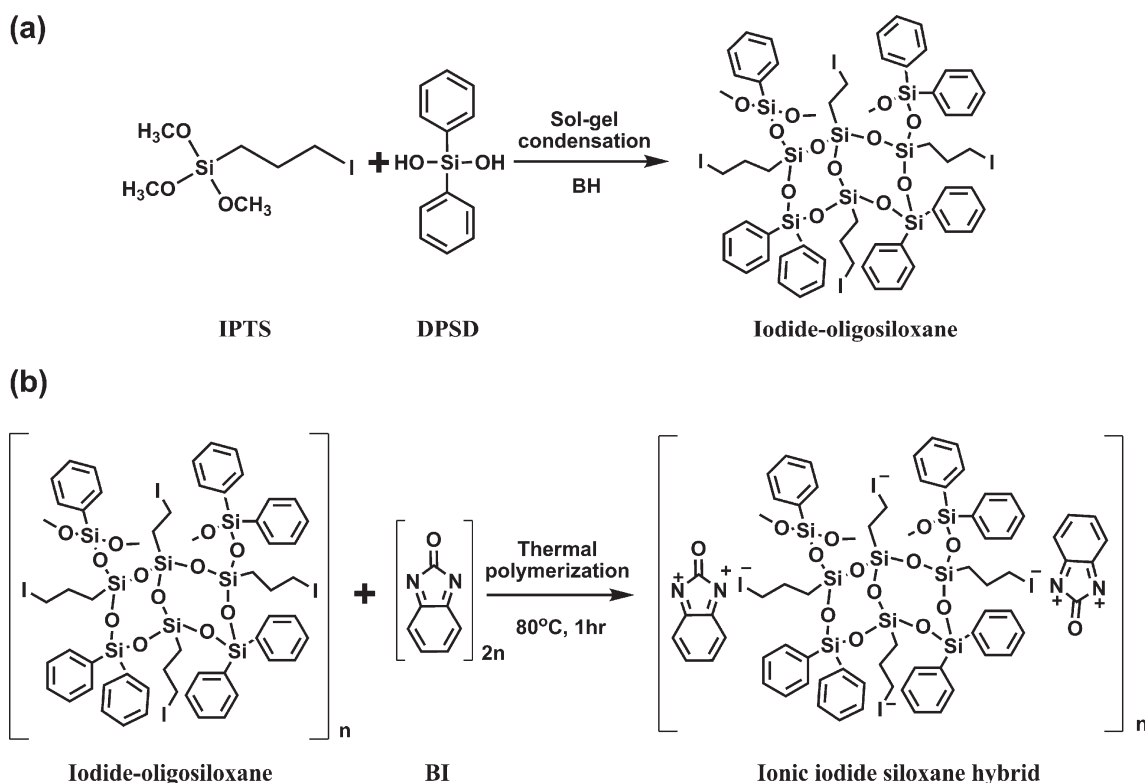
state electrolytes, the solar to electricity conversion efficiencies are decreased relative to those of corresponding liquid electrolyte DSSC. This lowered solar to electricity conversion efficiency is attributed to a decrease in the mobility of ions in the electrolytes and poor permeation of the quasi-solid state electrolyte into the pores of the  $\text{TiO}_2$  layers, because of its viscous nature. Given this background, new and versatile materials with high ionic conductivity and stability are needed for application to quasi-solid state DSSCs. Nanosized fumed silica particles were used as gel liquid electrolytes by Grätzel et al.<sup>9</sup> Instead of fumed silica nanoparticles, a trimethoxysilane-derived ionic liquid synthesized by a hydrolytic sol–gel reaction has been studied as a gel electrolyte in DSSCs, yielding a solar to electricity conversion efficiency of over 5%.<sup>10</sup> Tetramethyl orthosilicate (TMOS) and tetraethyl orthosilicate (TEOS), which can be formed silica

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Scheme 1. Schematic Diagram of (a) the Synthesis of the Iodide-Oligosiloxanes by a Sol–Gel Condensation of IPTS and DPSD and (b) Fabrication of Ionic Iodide Hybrid by Thermal Polymerization of Iodide-Oligosiloxanes with BI



nanoparticles by a hydrolytic sol–gel reaction, were also used as a gelator to support the electrolyte.<sup>11,12</sup> However, water is required to form the siloxane network by a hydrolytic sol–gel reaction of alkoxy silanes in order to increase the viscosity of the electrolyte. The residual water is a source of condensation between the silane precursors and adsorbs into the pores of the TiO<sub>2</sub> films, thereby degrading the photovoltaic characteristics and induces poor stability.

Nonhydrolytic sol–gel-derived siloxane-based organic–inorganic hybrid materials, in which inorganic networks such as siloxane bonds can form by a simple condensation reaction without water, have been widely studied for many applications.<sup>13–16</sup> With a suitable selection of precursors and optimization of processing parameters, the organic moieties, size, and molecular weight of oligosiloxane can be controlled. In addition, they show high thermal and chemical stability due to the existence of siloxane bonds, and high shelf stability due to the absence of water molecules and hydroxyl groups.

In this study, we report on a new type of ionic iodide-siloxane hybrid materials produced by polymerization of sol–gel synthesized iodide-oligosiloxane resins to be used as a gelator and also ionic liquid of the electrolyte in a DSSC. The molecular structures and sizes of the synthesized oligosiloxanes can be modulated by changing the composition ratio of the silane precursors. A DSSC using the fabricated ionic iodide-siloxane hybrid electrolyte exhibits high solar to electricity conversion efficiency of up to 5% at 1 sunlight (100 mW cm<sup>-2</sup>). Scheme 1 chemically illustrates of (a) the synthesis of iodide-oligosiloxanes by sol–gel condensation of 3-iodopropyltrimethoxysilane (IPTS) and diphenylsilanediol (DPSD), and (b) the fabrication of ionic iodide-siloxane hybrid materials by thermal polymerization of the

Table 1. Compositions of Silane Precursors for Synthesis of the Iodide-Oligosiloxanes

| notation | IPTS (mol) | DPSD (mol) | Ba(OH) <sub>2</sub> H <sub>2</sub> O (mol) |
|----------|------------|------------|--|
| ID33     | 0.067      | 0.033      | 0.0002                                     |
| ID41     | 0.059      | 0.041      | 0.0002                                     |
| ID50     | 0.050      | 0.050      | 0.0002                                     |

iodide-oligosiloxanes with 2-benzimidazolone (BI). In the sol–gel condensation step, hydroxyl groups in DPSD and alkoxy groups in IPTS are directly condensed to form siloxane bonds without using water. In this stage, the viscosity of sol–gel condensed oligosiloxanes is low because of their oligomeric molecular structure. The ionic iodide-siloxane hybrid materials are fabricated by thermal polymerization between iodide groups in the oligosiloxanes with the chemical reaction between the iodide groups of the oligosiloxanes and BI and also the viscosity of the hybrid electrolyte is dramatically increased because of the formation of organic networks. This viscosity change behavior of the ionic iodide siloxane hybrid electrolyte is very useful for the fabrication of the DSSCs with gel electrolyte because the flowing electrolyte can be easily injected into the cell and the pores of TiO<sub>2</sub> films and the gel electrolyte formed by a thermal polymerization inside the cell with a homogeneous dispersion.

## EXPERIMENTAL SECTION

**Synthesis and Characterization of Iodide-Oligosiloxane Resins.** The iodide-oligosiloxanes were synthesized by a sol–gel

condensation reaction between 3-iodopropyltrimethoxysilane (IPTs, Fluka, USA) and diphenylsilanediol (DPSD, Gelest, USA) in the presence of barium hydroxide monohydrate (BH, Aldrich, USA) as a catalyst with 0.2 mol % equivalents of the total silane precursors. The condensation process by BH promotes a chemical reaction between the precursors fast and result in highly condensed oligomeric species.<sup>13,14</sup> All the chemicals were used as received without purification. The precursor silane compositions were varied from 33 to 50 mol % of DPSD to prepare three different composition samples. The compositions and notations of the samples are listed in Table 1.

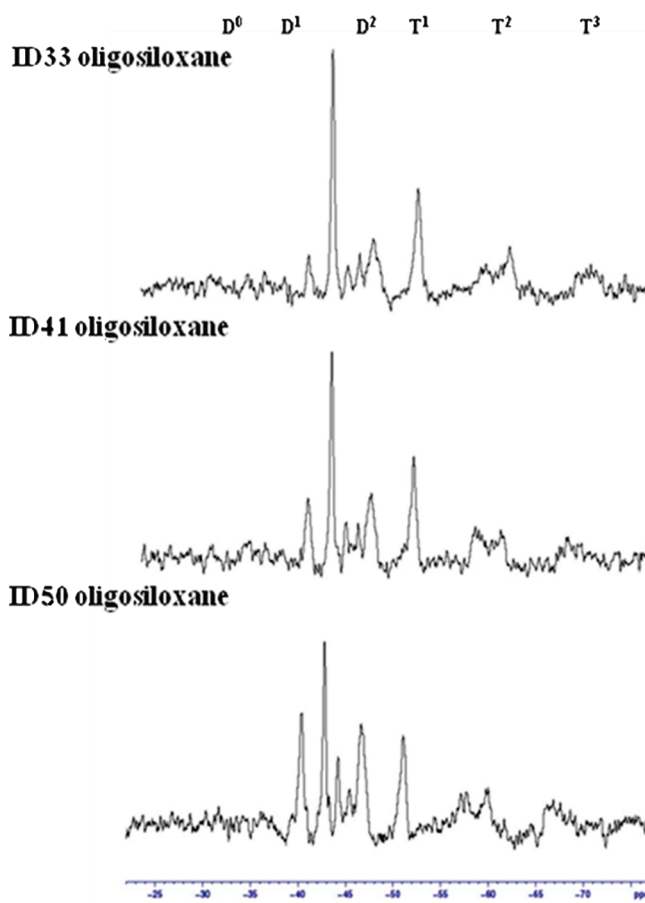
For a homogeneous condensation reaction between the two silane precursors, solid-state DPSD was continuously added to the IPTs and BH liquid mixture in a flask while stirring the solution with a magnetic stirrer at 80 °C for 2 h to promote the chemical reaction. The resulting solution was then mixed for an additional 2 h to complete the condensation reaction. Methanol, a byproduct of the condensation, was removed by vacuum heating. Although BH is insoluble in water and any alcohol, the remaining BH was removed using a 0.45  $\mu\text{m}$  pore-sized Teflon filter. Finally, a clear, brown-colored solution of iodide-oligosiloxane resin was obtained.

Fourier transform infrared (FTIR, JASCO, USA) spectra of the iodide-oligosiloxanes were obtained with a resolution of 4  $\text{cm}^{-1}$  in a wavenumber range 400–4000  $\text{cm}^{-1}$ .  $^{29}\text{Si}$  nuclear magnetic resonance (NMR, Bruker, USA) spectra of the resin in chloroform-*d* were recorded using a Bruker FT 500 MHz instrument. The sample temperature was 300K and the pulse delays were set to 30 s. The distribution of molecular species in the iodide-oligosiloxane resins was examined by matrix-assisted laser desorption and ionization time-of-flight mass spectrometry (MALDI-TOF MS, PerSeptive Biosystems, USA). The spectra of MALDI-TOF MS were obtained with a Voyager-DE STR 4700 proteomics analyzer equipped with a nitrogen laser using a wavelength of 337 nm and a pulse width of 3 ns. The iodine absorption spectra were obtained using a UV/vis/NIR spectrophotometer (Shimadzu, Japan). Differential scanning calorimetry (DSC, NETZSCH) measurements were performed under a nitrogen atmosphere at a heating rate of 5 °C  $\text{min}^{-1}$  to confirm thermal curing behavior of the iodide-oligosiloxanes with BI in the electrolytes. *J*–*V* characteristics were measured using a Keithley 2400 source meter. A 1000 W xenon lamp (Oriel, 91193) served as the light source. The light intensity was adjusted with a reference Si cell (Fraunhofer Institute for Solar Energy System) to 1 sun light intensity of 100  $\text{mW}/\text{cm}^2$ .

#### Fabrication of Ionic Iodide-Siloxane Hybrid Electrolyte.

The synthesized oligosiloxane resins were cured by heating at 80 °C for 1 h by addition of the 2-benzimidazolone (BI) with a 1:1 molar ratio to iodide-oligosiloxanes. For application as an electrolyte in a DSSC, LiI (Aldrich, USA), 4-*tert*-butylpyridine (TBP, Aldrich, USA), and I<sub>2</sub> (Aldrich, USA) were added to the oligosiloxane resins in 3-methoxypropionitrile (3-MPN, Fluka, USA). LiI can provide small ions to the electrolyte and TBP prevent recombination of electrons near dye and TiO<sub>2</sub> surface.<sup>17</sup> Consequently, they can increase the ionic conductivity and open-circuit voltage. Five different oligosiloxane resin mixtures were prepared: (a) 0.6 M concentration of ID33, (b) ID41, and (c) ID50 oligosiloxane to investigate the effect of the molecular structure, and (d) 0.2 M and (e) 1.0 M concentrations of ID33 oligosiloxane in 3-MPN with the 0.1 M LiI, 0.5 M TBP, and 0.05 M I<sub>2</sub> concentration to optimized the concentration of the electrolyte. For comparison, a reference liquid electrolyte (r) comprising 0.6 M 1-hexyl-2,3-dimethylimidazolium iodide (HDMII, C-TRI, Korea), 0.1 M LiI, 0.5 M TBP, and 0.05 M I<sub>2</sub> in 3-MPN was employed.

**Fabrication and Characterization of DSSC.** FTO glass was cleaned with ultrasonification in DI water and ethanol. After drying at 70 °C, a thin buffer TiO<sub>2</sub> layer was deposited using 2 M TiCl<sub>4</sub> solution by spin-coating and annealed at 500 °C for 30 min after cleaning in DI water and ethanol. Titania paste (Dyesol Ltd. Australia), was deposited



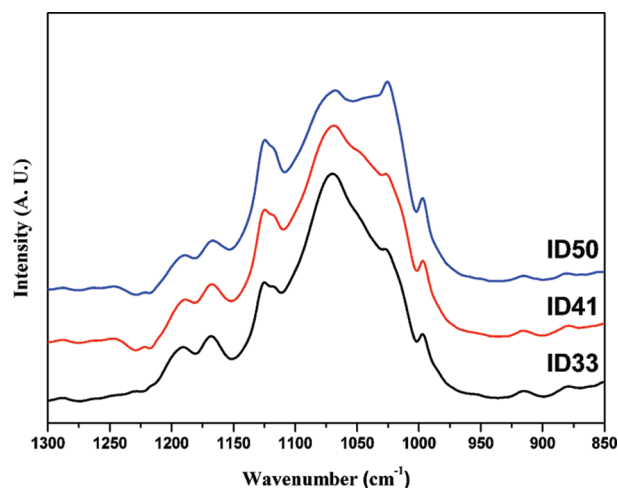
**Figure 1.**  $^{29}\text{Si}$  NMR spectra of the iodide-oligosiloxane resins synthesized by sol–gel condensation of different compositions of IPTs and DPSD.

on the above pretreated FTO glass as a working electrode using the doctor blade technique.<sup>18</sup> The film was dried for 20 min at 70 °C, and then coated with 2 M TiCl<sub>4</sub> solution via spin-coating followed by annealing at 450 °C for 30 min. A porous TiO<sub>2</sub> film with a thickness of about 15 nm was thus produced. TiO<sub>2</sub>-coated FTO glass was immersed in an anhydrous ethanolic solution of 0.3 mM N719 dye (Solaronix SA, Swiss) at room temperature for 24 h. A counter electrode was prepared with 5 mM hydrogen hexachloroplatinate(IV) hydrate (H<sub>2</sub>PtCl<sub>6</sub>·H<sub>2</sub>O) in 2-propanol via spin-coating, followed by drying and annealing at 450 °C for 30 min. The photoelectrode and counter-electrode were sealed with a Surlyn (Solaronix SA, Swiss) under pressure at 100 °C. The electrolyte solution was introduced into the cell through one of two small holes drilled in the counter electrode. The holes were then covered and sealed with a Surlyn and cover glass. A solution comprised of iodide-oligosiloxane, LiI, TPB, and I<sub>2</sub> as well as the reference solution (HDMII, LiI, TBP, and I<sub>2</sub>) were introduced into the cell. The iodide-siloxane hybrid electrolyte was formed in situ by heating the oligosiloxane resin containing the DSSC at 80 °C for 1 h.

## RESULTS AND DISCUSSION

### Characterization of Synthesized Iodide-Oligosiloxanes.

The structure of the iodide-oligosiloxane resin was characterized by  $^{29}\text{Si}$  NMR and FT-IR spectroscopy. In NMR notation, for D<sup>*n*</sup> and T<sup>*n*</sup>, the superscript “*n*” denotes the number of bridging oxygen atoms to a Si atom. Depending on the composition of the reactants, different siloxane bonds are formed. As show



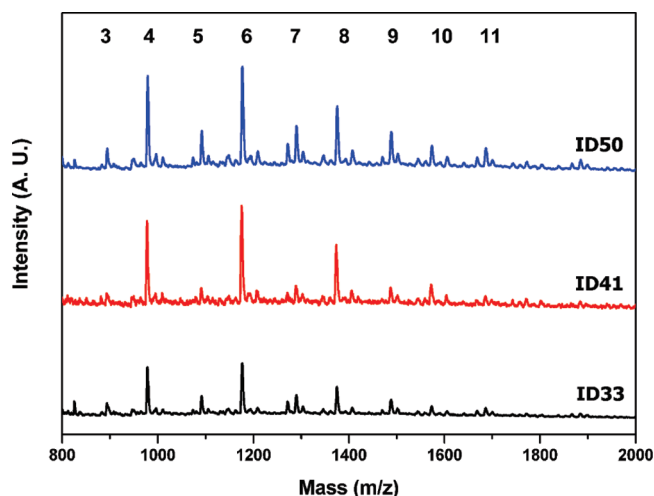
**Figure 2.** FT-IR spectra of the iodide-oligosiloxane resins synthesized by nonhydrolytic sol-gel condensation of different compositions of IPTS and DPSD.

in Figure 1,  $D^2$ ,  $T^2$ , and  $T^3$  peaks are enhanced as the DPSD content in the reactants increases.<sup>13,14</sup> Also, small amounts of unreacted Si species ( $D^0$ : 29 and 34 ppm), which are not desirable for the synthesis of oligosiloxanes, are detected in all the spectra. The  $D^0$  peak at 29 ppm is found in the form of diphenylmethoxysilanol or diphenyldimethoxysilane, which is a product of the reaction between DPSD and methanol. However, very small  $D^0$  peak at 34 ppm representing DPSD is found. The hydroxyl groups of DPSD, highly reactive radicals to water molecules, can be deteriorated the shelf stability of the electrolyte. This means that the condensation reaction between IPTS and DPSD proceeded well, and that the iodide-oligosiloxanes were successfully synthesized using a nonhydrolytic sol-gel reaction. Theoretically,  $T^3$  species are not formed in the condensation reaction due to the diol radical in the reactants. However, the  $T^3$  peak is present in the spectra. This might be due to a re-esterification reaction of the methoxy group in the IPTS. Water, which is a byproduct of the condensation reaction between diol and methanol, produces  $T^2$ -OH by hydrolysis of the methoxy group in IPTS. Thus, the self-condensation reaction of  $T^2$ -OH species can form  $T^3$  species. Consequently, the degree of condensation (DOC) depending on the DPSD content in the reactants can be calculated using the following equation<sup>19</sup>

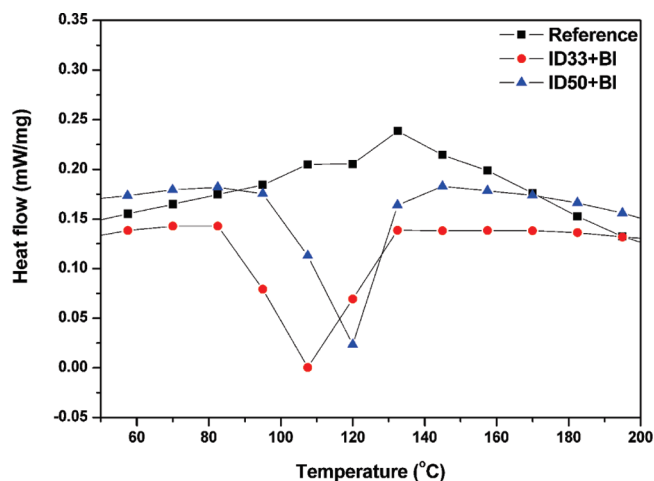
$$\text{DOC} = \frac{D^1 + 2D^2 + T^1 + 2T^2 + 3T^3}{2(D^0 + D^1 + D^2) + 3(T^0 + T^1 + T^2 + T^3)} \times 100$$

It is found that the DOC increases from about 60 to 80% as the DPSD content is increased from 33 to 50%.

In the FT-IR spectra (Figure 2), Si-O stretching vibrations were observed at  $1025 \text{ cm}^{-1}$ , and Si-O-Si groups were observed at  $1075 \text{ cm}^{-1}$  for asymmetric bonds and  $1115 \text{ cm}^{-1}$  for cage structure<sup>20</sup>. The peaks of the Si-O-Si asymmetric stretching mode appeared at  $1110$  and  $1065 \text{ cm}^{-1}$  in the iodide-oligosiloxane resins. This indicates that a direct condensation reaction between DPSD and IPTS was achieved. Also, there were only small amount of silanol groups and unreacted precursors, thereby preventing further self-condensation of the resin. With an increase in DPSD content, the peak of the Si-O-Si stretching mode increases. This means that, ID50 oligosiloxane consist of more condensed molecules as compared to ID33 oligosiloxane.



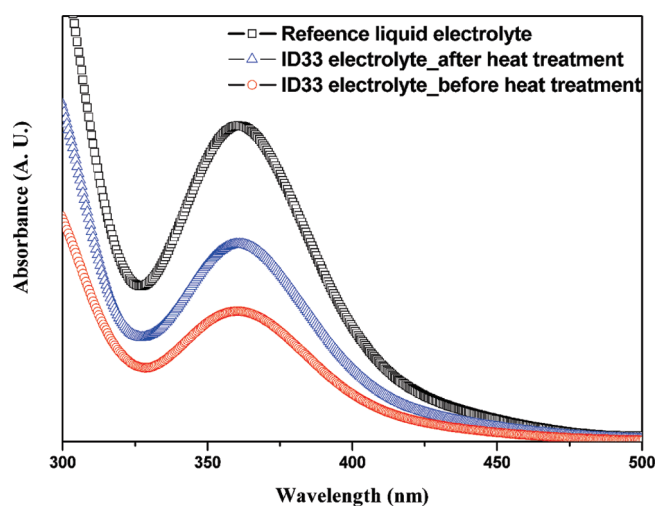
**Figure 3.** MALDI-TOF MS spectra of the iodide-oligosiloxane resins with various compositions. Peaks corresponding to trimer, tetramer, pentamer, hexamer, heptamer, octamer, nonamer, decamer, and hendecamer are represented, respectively.



**Figure 4.** DSC curves of ID33 oligosiloxane and ID50 oligosiloxane resins with BI and reference liquid electrolyte (mixture of HDMII, LiI, and  $I_2$  in 3-MPN).

We measured MALDI-TOF MS to support the NMR and FT-IR results and confirm that the ID50 oligosiloxane composition includes species with high molecular weights. Figure 3 presents the results of the MALDI-TOF MS of iodide-oligosiloxane resins synthesized with various silane precursor compositions. The structure of the iodide-oligosiloxane resins for all compositions is mainly tetramer, a reaction product of four identical silane precursors. The MALDI-TOF MS peaks of the ID50 oligosiloxane resin are shifted to peaks of species with high molecular weights compared to those of the ID33 oligosiloxane resin.

The results of NMR, FT-IR, and MALDI-TOF MS indicate that higher DPSD content in the iodide-oligosiloxanes results in is associated with lower iodide groups in unit molecular weight. Therefore, ID50 oligosiloxane requires more weight for the same iodide molar ratio in the electrolyte than ID33 oligosiloxane does. Also, the viscosity of the iodide-oligosiloxanes is increased with DPSD contents.

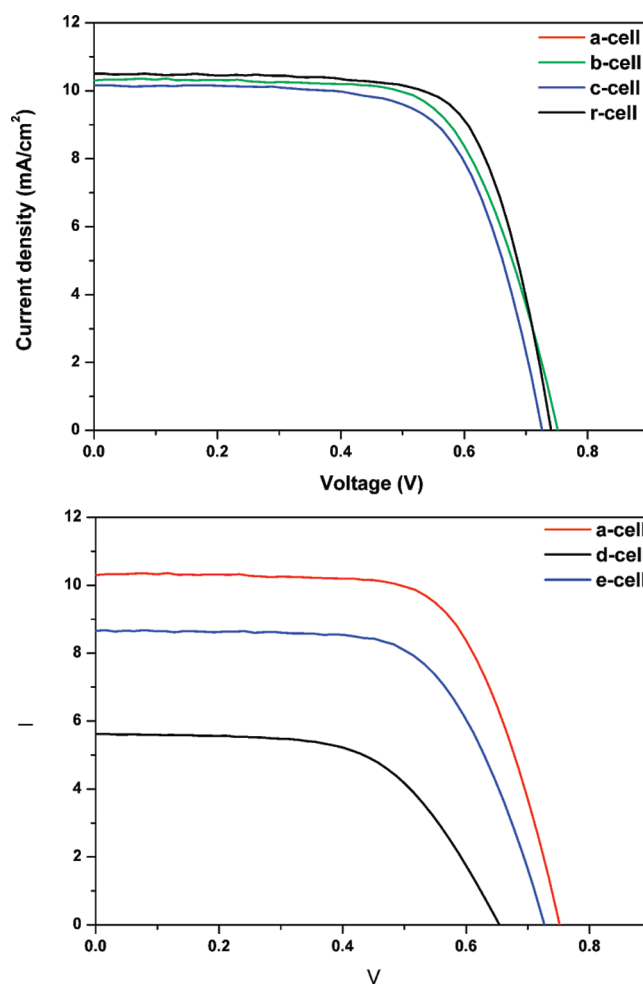


**Figure 5.** Absorption spectra of mixed solution of ID33 oligosiloxane resin, LiI, and  $I_2$  with BI in 3-MPN before and after thermal curing at 80 °C for 1 h comparing with liquid reference electrolyte (mixture of HDMII, LiI, and  $I_2$  in 3-MPN).

**Fabrication of Iodide-Siloxane Hybrid Materials.** The polymerization of iodide groups in oligosiloxanes with BI was confirmed by DSC for the fabrication of homogeneous gel electrolytes. As represented in Figure 4, there was no exothermic peak in the reference liquid electrolyte, which presents only a broad endothermic peak resulting from solvent evaporation in the liquid reference electrolyte. However, an exothermic peak is observed for the mixture of ID33 oligosiloxane and BI in a temperature range between 55 and 88 °C, with a peak maximum at 71 °C. For the mixture of ID50 oligosiloxane and BI, an exothermic peak is shown between 64 and 96 °C with a peak maximum at 80 °C. Thus, it is confirmed that the iodide-oligosiloxanes are polymerized at 80 °C with the BI, which is a suitable curing agent of iodide-oligosiloxanes, as well as an iodide ion generator. The maximum thermal curing peak position for ID33 oligosiloxane is lower than for that for the ID50 oligosiloxane, because more iodide groups per unit mass are contained in the former.

Evidence of the production of  $I_3^-$  during the thermal polymerization of the iodide-oligosiloxane was found in the UV/vis/NIR spectra (Figure 5), which presents the absorption spectra of a mixed solution of ID33 oligosiloxane, LiI, and  $I_2$  with BI in 3-MPN, before and after heat-treatment at 80 °C for 1 h in comparison with the reference liquid electrolyte (HDMII, LiI, and  $I_2$  in 3-MPN). The produced  $I_3^-$  will be the main ionic conductivity vehicle through the reaction  $I_3^- + 2e^- \rightarrow 3I^-$  on the counter electrode in the DSSC. The absorption peaks at 300 and 360 nm are due to  $I_3^-$ , whereas that at 500 nm is a result of  $I_2^{21}$ . All the samples show peaks of  $I_3^-$  but no peaks of  $I_2$ . The characteristic  $I_3^-$  peak at 360 nm is clearly higher in the heat-treated oligosiloxane sample than the unreacted sample because the generation of  $I^-$  is promoted the chemical reaction between iodide groups in oligosiloxanes and BI by a heat treatment, although it is lower than that of the reference liquid electrolyte. This indicates that the iodide-oligosiloxanes creates  $I_3^-$  during the thermal polymerization between iodide-oligosiloxanes and BI.

**Photovoltaic Characteristics of DSSC Using Iodide-Oligosiloxane Hybrid Electrolyte.** DSSCs using the fabricated



**Figure 6.**  $J$ - $V$  curves of the DSSC using hybrid electrolytes with different composition and concentration of the iodide-oligosiloxanes; 0.6 M concentration of (a) ID33, (b) ID41, and (c) ID50 oligosiloxane, and (d) 0.2 and (e) 1.0 M concentrations of ID33 oligosiloxane, while keeping the LiI, TBP, and  $I_2$  concentrations in 3-MPN constant. Also, the reference liquid electrolyte (r) composed of 0.6 M HDMII, LiI, TBP, and  $I_2$  was used for the comparison. The light intensity was 100 mW  $cm^{-2}$ .

iodide-oligosiloxane hybrid electrolytes were fabricated and their efficiencies were examined. Five different hybrid electrolytes with various oligosiloxane compositions and concentrations in 3-MPN were prepared; 0.6 M concentration of (a) ID33, (b) ID41, and (c) ID50 oligosiloxane, and (d) 0.2 and (e) 1.0 M concentrations of ID33 oligosiloxane with the 0.1 M LiI, 0.5 M TBP, and 0.05 M  $I_2$  concentrations. Also, a reference liquid electrolyte (r) composed of 0.6 M HDMII, 0.1 M LiI, 0.5 M TBP, and 0.05 M  $I_2$  was used for comparison. The photovoltaic characteristics of the DSSCs with different hybrid electrolytes and liquid reference electrolyte are presented in Figure 6 and the results are summarized in Table 2. The a, b, and c cells with different oligosiloxane compositions present an open-circuit voltage ( $V_{oc}$ ) of 0.76, 0.73 and 0.73 V, a short-circuit current density ( $J_{sc}$ ) of 10.30, 10.16 and 10.04  $mAcm^{-2}$ , and a fill factor (ff) of 0.68, 0.67, and 0.67, respectively. The cell with the hybrid electrolyte cured by ID33 oligosiloxane having more iodide and smaller siloxane size than the others shows higher  $V_{oc}$  and  $J_{sc}$ . Also, the smaller molecular weight of ID33 oligosiloxane results in a smaller portion of siloxane bonds, lower viscosity, and fewer

**Table 2. Photovoltaic Characteristics of the DSSCs fabricated Using Different Hybrid Electrolytes Comparing with Reference Liquid Electrolyte; Light Intensity Was 100 mW cm<sup>-2</sup>**

| cell <sup>a</sup> | V <sub>oc</sub> (V) | J <sub>sc</sub> (mAcm <sup>-2</sup> ) | ff   | η (%) |
|-------------------|---------------------|---------------------------------------|------|-------|
| r                 | 0.74                | 10.5                                  | 0.71 | 5.5   |
| a                 | 0.76                | 10.30                                 | 0.68 | 5.2   |
| b                 | 0.73                | 10.16                                 | 0.67 | 5.0   |
| c                 | 0.73                | 10.04                                 | 0.67 | 4.9   |
| d                 | 0.65                | 5.63                                  | 0.59 | 2.3   |
| e                 | 0.73                | 8.65                                  | 0.65 | 4.2   |

<sup>a</sup> r (reference liquid electrolyte) 0.6M HDMII, 0.1M LiI, 0.5M TBP, and 0.05M I<sub>2</sub> in 3-MPN. a, 0.6M ID33; b, 0.6M ID41; c, 0.6M ID50; d, 0.2M ID33; and e, 1.0M ID33 with 0.1M LiI, 0.5M TBP, and 0.05M I<sub>2</sub> in 3-MPN.

bulky phenyl groups in the hybrid electrolyte, thereby promoting mobility within the iodide-siloxane structure. The performance of the DSSC is significantly affected by the viscosity of the electrolyte and molecular mobility.<sup>22</sup> Thus, the a-cell shows better photovoltaic characteristics than the others. For the optimization of the concentration of the iodide-oligosiloxane in the electrolyte, we measure the photovoltaic characteristics of the different concentration of ID33 oligosiloxane. The d and e-cells show a poor performance relate to the a cell (V<sub>oc</sub> of 0.65 and 0.73 V, a J<sub>sc</sub> of 5.63 and 8.65 mAcm<sup>-2</sup>, and a ff of 0.59 and 0.65 for d and e cell, respectively). The hybrid electrolyte with 0.6 M concentration of oligosiloxane provides optimized performance in the DSSC. Thus, the cell with the hybrid electrolyte cured by ID33 oligosiloxane with 0.6 M concentration in 3-MPN exhibits the best performance with the highest solar to electricity conversion efficiency (5.22%) at 1 sunlight (100 mW cm<sup>-2</sup>). (Note that the cell with the reference liquid electrolyte exhibited efficiency 5.5%.) Thus, the DSSC with the iodide-oligosiloxane hybrid electrolyte fabricated by thermal polymerization of iodide-oligosiloxane presents comparable solar to electricity conversion efficiency to the cell with the reference liquid electrolyte. It is expected that the use of this iodide-siloxane hybrid electrolyte will produce more stable and reliable DSSCs because of its quasi-solid state and hybrid characteristics.

## CONCLUSION

Iodide-oligosiloxane resins were synthesized by nonhydrolytic sol-gel condensation of IPTS and DPSD and their molecular structures were characterized. The oligosiloxanes were thermally polymerized with BI, a curing agent, as well as an ionic iodide generator, at 80 °C for 1 h to fabricate the iodide-siloxane hybrid electrolyte for the DSSC. Smaller-molecular-size oligosiloxane with greater iodide content may promote ionic mobility in the hybrid electrolyte. The DSSC with an optimized quasi-solid state hybrid electrolyte exhibited high energy conversion efficiency of 5.2%, which approaches that of the cell with the reference liquid electrolyte.

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