Fabrication of Perovskite-Type Photovoltaic Devices with Polysilane Hole Transport Layers

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Abstract

Perovskite-type photovoltaic devices with polysilane hole transport layers were fabricated by a spin-coating method. In the present work, poly(methyl phenylsilane) (PMPS) and decaphenylcyclopentasilane (DPPS) were used as the hole transport layers. First, structural and optical properties of the PMPS and DPPS films were investigated, and the as-prepared PMPS and DPPS films were amorphous. Optical absorption spectra of the amorphous PMPS and DPPS showed some marked features due to the nature of polysilanes. Then, microstructures, optical and photovoltaic properties of the perovskite-type photovoltaic devices with polysilane hole transport layers were investigated. Current density-voltage characteristics and incident photon to current conversion efficiency of the photovoltaic devices with the polysilane layers showed different photovoltaic performance each other, attributed to molecular structures of the polysilanes and Si content in the present hole transport layers.

Keywords

Polysilane, Hole Transport Layer, Perovskite, Photovoltaic Device

1. Introduction

Since the first report of solar cells based on organic-inorganic halide perovskites [1], various perovskite-type solar cells consisting of ABX₃ compounds (A = CH₃NH₃, HC(NH₃)₂ or Cs, B = Pb or Sn, X = I, Cl or Br) have been extensively studied [2]-[7]. Conversion efficiencies over 20% have recently been achieved for perovskite-type solar cells [8]-[13]. However, photovoltaic properties of perovskite-type solar cells strongly depend on fabrication process, microstructure and electronic structure of materials. For perovskite-type solar cells, instabilities against humidity, temperature, and continuous light irradiation are also
crucial issue [14]. Therefore, detailed investigation of perovskite-type solar cells is required to achieve conversion efficiency greater than currently achieved.

2,2',7,7'-tetrakis[N,N-di(p-methoxyphenyl)amino]-9,9'-spirobifluorene (spiro-OMeTAD) is used in perovskite-type solar cells as a hole transport layer because spiro-OMeTAD can yield high conversion efficiency. However, spiro-OMeTAD is an expensive organic compound. To circumvent the problem, exploitation of alternate hole transport materials has actually been performed [15] [16] [17] [18].

Polysilanes are promising candidates for the alternate hole transport materials because they are one-dimensional silicon-based materials [19] [20], and can provide good electrical, optical and photovoltaic properties [21] [22] [23] [24]. Very recently, effects of polysilane-doped spiro-OMeTAD hole transport layers were investigated by our group, and the polysilane-doped spiro-OMeTAD hole transport layers were found to increase conversion efficiency of the perovskite-type photovoltaic devices [25]. However, photovoltaic properties of perovskite-type solar cells with polysilanes as hole transport layers have not yet been clarified.

The purpose of the present work is to fabricate of perovskite CH₃NH₃PbI₃-based photovoltaic devices with polysilane hole transport layers. In the present study, poly(methyl phenylsilane) (PMPS) and decaphenylcyclopentasilane (DPPS) were used as the hole transport layers, as shown in Figure 1(a) and Figure 1(b), respectively. The photovoltaic devices with the polysilane layers were fabricated by a simple spin-coating method in air atmosphere. Structures, optical and photovoltaic properties of the polysilanes and CH₃NH₃PbI₃ were also investigated. The structures and optical properties of the polysilanes and CH₃NH₃PbI₃ were investigated by X-ray diffraction (XRD), scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS) and optical spectroscopy. Besides, the photovoltaic properties of the devices were evaluated by measuring current density-voltage (J-V) characteristics and incident photon to current conversion efficiency (IPCE). Carrier transport mechanism based on the obtained results was discussed.

Figure 1. Molecular structures of (a) PMPS and and (b) DPPS.
2. Experimental Procedures

First, polysilane films were prepared on cleaned glass substrates by a spin-coating method [26]. PMPS (Osaka Gas Chemicals, OGSOL SI-10-10, molecular weight (Mw): 16,300, 12 mg) and DPPS (Osaka Gas Chemicals, OGSOL SI-30-10, Mw: 945.11, 12 mg) powders were separately dissolved in o-dichloro-benzene (Wako Pure Chemical Industries, 500 μL). Triphenylborate solution (Sigma-Aldrich, 25 μL) was added into the polysilane solutions as a p-type dopant [26]. Non-doped and boron (B)-doped polysilane solutions were stirred at room temperature. The polysilane solutions were dropped on the glass substrates, and spun by a spin coater (Mikasa, MS-A 100) at 1500 rpm for 30 s. This process was repeated until the desired thickness. Then, CH$_3$NH$_3$PbI$_3$-based photovoltaic devices with polysilane hole transport layers were also fabricated to investigate photovoltaic properties of the polysilanes. The detailed fabrication process was described in our previous reports [18] [25] [27] [28] [29] [30], except for those of CH$_3$NH$_3$PbI$_3$ and polysilane layers. In the present work, 0.15 and 0.30 M compact TiO$_x$ precursor solutions were prepared from titanium diisopropoxide bis(acetyl-acetonate) (Sigma-Aldrich, 0.055 mL and 0.11 mL) and 1-butanol (Nacalai Tesque, 1 mL). The 0.15 M TiO$_x$ precursor layer was spin-coated onto cleaned fluorine (F)-doped tin oxide (FTO) substrate by the spin coater at 3000 rpm for 30 s. After that, the TiO$_x$ was dried on a hot plate (As One, ND-1) at 125°C for 5 min. Likewise, the 0.30 M TiO$_x$ precursor layer was spin-coated onto the 0.15 M TiO$_x$ layer at 3000 rpm for 30 s, and dried at 125°C for 5 min. This process was repeated twice. Finally, the TiO$_x$ layer was annealed in an electric furnace (as one, SMF-1) at 500°C for 30 min. After cooling to room temperature, mesoporous TiO$_2$ layer was spin-coated onto the compact TiO$_2$ layer at 5000 rpm for 30 s, and was dried on the hot plate at 125°C for 5 min. The mesoporous TiO$_2$ layer was sintered in the electric furnace at 500°C for 30 min. Prior to spin-coating of the mesoporous TiO$_2$, the TiO$_2$ paste was prepared by dispersing TiO$_2$ powder (Aerosil, P-25) in ultrapure water. Poly(ethylene glycol) (Nacalai Tesque, averaged molecular number: 20,000, 10 mg), acetylacetone (Wako Pure Chemical Industries, 10 μL) and a surfactant (Sigma-Aldrich, Triton X-100, 5 μL) were added in the TiO$_2$ paste. The paste was stirred for 30 min, and was left overnight without stirring. For preparation of CH$_3$NH$_3$PbI$_3$ layers, a combination of a one-step solution deposition method [18] [25] [27] [28] [29] [30] [31] and hot air flow-assisted spin-coating technique [17] [32] was adopted in the present work. The preparation process of the CH$_3$NH$_3$PbI$_3$ layers were as follows: CH$_3$NH$_3$I (Showa Chemical, 99.8 mg) and PbI$_2$ (Sigma-Aldrich, 289.3 mg) were dissolved in a mixed solvent consisting of γ-butyrolactone (Wako Pure Chemical Industries, 300 μL) and N,N-dimethylformamide (DMF) (Nacalai Tesque, 200 μL) [33]. The molar ratio of the solutes was 1:1. The CH$_3$NH$_3$PbI$_3$ solution was stirred at 60°C over 2 h. Prior to spin-coating, the solution was filtered using a 0.20 μm poly(vinylidene difluoride) syringe filter unit (Advantec, Dismic 13 HP). Moreover, the substrate was kept at 50°C by a heating gun, checked by a thermometer. The CH$_3$NH$_3$PbI$_3$ solution was immersed into the
mesoporous TiO$_2$ layer, and was spun at 2000 rpm for 60 s. During the spin-coating, hot air from the heating gun was continuously flown. The spin-coated CH$_3$NH$_3$PbI$_3$ layer was then annealed on the hot plate at 100°C for 1 min. After that, B-doped PMPS (PMPS:B) and DPPS (DPPS:B) solutions were dropped onto the CH$_3$NH$_3$PbI$_3$ layers, and were spun at 1500 rpm for 30 s without hot air flow. The spin-coating process was repeated twice. Finally, gold (Au) electrodes were deposited onto the polysilane layers by a vacuum evaporation system (Sanyu Electron Co., Ltd., SVC-700TM/SVC-700-2). The present photovoltaic devices are denoted as FTO/TiO$_2$/CH$_3$NH$_3$PbI$_3$/PMPS:B or DPPS:B/Au.

The PMPS, PMPS:B, DPPS and DPPS:B films were characterized by an X-ray diffractometer (Bruker Corporation, D2 PHASER). Optical absorption spectra of the polysilane films were collected by an ultraviolet-visible-near infrared (UV-VIS-NIR) spectrometer (Jasco Corporation, V-770). The CH$_3$NH$_3$PbI$_3$ layers in the FTO/TiO$_2$/CH$_3$NH$_3$PbI$_3$/PMPS:B/Au and FTO/TiO$_2$/CH$_3$NH$_3$PbI$_3$/DPPS:B/Au devices were also evaluated by XRD and SEM (Jeol Ltd., JSM-6010PLUS/LA) attached with an EDS detector. The optical absorption spectra of the CH$_3$NH$_3$PbI$_3$ in the photovoltaic devices with the polysilane hole transport layers were collected using the UV-VIS-NIR spectrometer. The J-V characteristics of the FTO/TiO$_2$/CH$_3$NH$_3$PbI$_3$/PMPS:B/Au and FTO/TiO$_2$/CH$_3$NH$_3$PbI$_3$/DPPS:B/Au were measured using a potentiostat (Hokuto Denko Corporation, HSV-110) under simulated AM 1.5 (100 mW·cm$^{-2}$) irradiation conditions. The light was irradiated from the bottom side of FTO-coated glass substrate using a solar simulator (San-Ei Electric Co., Ltd., XES-301S). Effective area of the device was 0.090 cm$^2$. IPCE spectra of the devices were also collected using an IPCE measurement system (Enli Technology Co., Ltd., QE-R). All measurements were carried out at room temperature.

3. Results and Discussion

**Figure 2(a)** shows XRD patterns of as-prepared PMPS, PMPS:B, DPPS and DPPS:B films. Broad peaks around 24° were the signals from the sample holder. All the as-prepared films were amorphous. **Figure 2(b)** exhibited heat-treated PMPS, PMPS:B, DPPS and DPPS:B films. The heat treatment was carried out at 100°C for 10 min. The DPPS and DPPS:B films were crystallized, as shown in **Figure 2(b)**, which agreed with our previous report [26]. Compared with the XRD pattern of heat-treated DPPS film, a peak shift to lower diffraction angle was observed for the heat-treated DPPS:B one, suggesting a structural change of DPPS by B doping and heat trearment. On the other hand, the PMPS and PMPS:B films were not crystallized. In the present work, non-heated PMPS:B and DPPS:B hole transport layers were prepared on the CH$_3$NH$_3$PbI$_3$-based photovoltaic devices.

**Figure 3(a)** and **Figure 3(b)** show optical absorption spectra of the as-prepared PMPS, PMPS:B, DPPS and DPPS:B films. Absorption intensities of PMPS and PMPS:B films shown in **Figure 3(a)** were almost same regardless of B doping. Some marked features were observed at 223, 243, 340 and 435 nm for PMPS and PMPS:B films. The features at 223, 243 and 340 nm can be assigned...
Figure 2. XRD patterns of (a) as-prepared and (b) heat-treated polysilanes prepared on glass substrates.

Figure 3. Optical absorption spectra of (a) PMPS (dashed green line) and PMPS:B (solid blue line) films, and (b) DPPS (dashed black line) and DPPS:B (solid red line) films. Inset in (a) is enlarged optical absorption spectra of PMPS and PMPS:B films.

to Si-C bond-related transition [34], π-π* transition of phenyl group [35] and σ-σ* transition of polysilane chain [35], respectively. The feature at 435 nm shown in inset in Figure 3(a) was derived from charge transfer excitation [35]. In contrast, absorption intensity of DPPS:B film shown in Figure 3(b) was larger than that of DPPS one, which was presumably due to B doping. A marked feature was observed at 272 nm for the DPPS and DPPS:B films, which would be assigned to σ-σ* transition. From the edges of the σ-σ* transitions, energy gaps of the PMPS, PMPS:B, DPPS and DPPS:B films were estimated to be 3.49, 3.49, and 3.68 and 3.66 eV, respectively.

XRD patterns of FTO/TiO₂/CH₃NH₃PbI₃/PMPS:B/Au and FTO/TiO₂/CH₃NH₃PbI₃/DPPS:B/Au photovoltaic devices are shown in Figure 4. The diffraction peaks corresponding to CH₃NH₃PbI₃ with a cubic system (Pm₃m) were observed. Some sharp diffraction peaks of PbI₂ were simultaneously observed at 12.5° and 25.9°, assumed that phase separation of PbI₂ from CH₃NH₃PbI₃ occurred [27]. From the XRD patterns in Figure 4, lattice constants (a) and unit cell volumes (V) of the CH₃NH₃PbI₃ were estimated, as presented in Table 1. The a and V values of the
CH₃NH₃PbI₃ in the two devices were larger than those of our previous reports [25] [27] [28] [29] because these structural parameters strongly depend on growth conditions. Crystallite sizes (D) of the CH₃NH₃PbI₃ were estimated using Scherrer’s equation: D = 0.9λ/βcosθ. Here, λ, β and θ are the X-ray wavelength (0.154184 nm), full width at half maximum of diffraction peaks and Bragg angle, respectively. The D values presented in Table 1 were almost same regardless of difference in hole transport materials.

A SEM image of the FTO/TiO₂/CH₃NH₃PbI₃/PMPS:B/Au device is shown in Figure 5(a). Many diamond-, cross- and cubic-shaped grains with sizes of 15 - 30 nm were observed. Figure 5(b) represents an EDS spectrum for the FTO/TiO₂/CH₃NH₃PbI₃/PMPS:B/Au device. It was confirmed that Pb, I, Si and B were contained in the device. Ti and Sn respectively derived from TiO₂ and FTO were also detected. Elemental mapping images of Pb, I, Si and B in the device collected by EDS detector are shown in Figures 5(c)-(f), respectively. The contents of Pb, I, Si and B are presented in Table 2. The elemental mapping images clarified that the grains shown in Figure 5(a) were CH₃NH₃PbI₃ because distribution of Pb and I atoms corresponded to the grains. Simultaneously, it was confirmed that Si and B atoms in the PMPS:B were distributed all over the CH₃NH₃PbI₃ layer. However, content of B was below detection limit (BDL).

Likewise, a SEM image of the FTO/TiO₂/CH₃NH₃PbI₃/DPPS:B/Au device is shown in Figure 6(a). Many cross-shaped grains with sizes of 20 - 40 nm were observed, considered that PMPS:B and DPPS:B affected surface morphology of

![Figure 4](image)

**Figure 4.** XRD patterns of FTO/TiO₂/CH₃NH₃PbI₃/PMPS:B/Au and FTO/TiO₂/CH₃NH₃PbI₃/DPPS:B/Au photovoltaic devices.

<table>
<thead>
<tr>
<th>Hole transport layer</th>
<th>a/nm</th>
<th>V/nm³</th>
<th>D/nm</th>
</tr>
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<tbody>
<tr>
<td>PMPS:B</td>
<td>0.6301 (3)</td>
<td>0.2500 (7)</td>
<td>104 ± 14</td>
</tr>
<tr>
<td>DPPS:B</td>
<td>0.6293 (3)</td>
<td>0.2492 (5)</td>
<td>102 ± 13</td>
</tr>
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Figure 5. (a) SEM image of CH$_3$NH$_3$PbI$_3$ surface in FTO/TiO$_2$/CH$_3$NH$_3$PbI$_3$/PMPS:B/Au photovoltaic device. (b) EDS spectrum for FTO/TiO$_2$/CH$_3$NH$_3$PbI$_3$/PMPS:B/Au device. (c)-(f) Elemental mapping images of (b) Pb M line, (c) I L line, (d) Si K line and (d) B K line.

CH$_3$NH$_3$PbI$_3$ because of their different molecular structures. An EDS spectrum for the FTO/TiO$_2$/CH$_3$NH$_3$PbI$_3$/DPPS:B/Au device is shown in Figure 6(b). Pb, I, Si and B atoms were confirmed as well as the FTO/TiO$_2$/CH$_3$NH$_3$PbI$_3$/PMPS:B/Au device. Elemental mapping images of Pb, I, Si and B in the device are shown in Figures 6(c)-(f). It is considered that the cross-shaped grains corresponded to CH$_3$NH$_3$PbI$_3$. The contents of Pb, I, Si and B are presented in Table 2. The content of Si in the FTO/TiO$_2$/CH$_3$NH$_3$PbI$_3$/DPPS:B/Au device was smaller than that in the FTO/TiO$_2$/CH$_3$NH$_3$PbI$_3$/PMPS:B/Au one. The difference would be attributed to molecular weight of the polysilanes.

Optical absorption spectra of the FTO/TiO$_2$/CH$_3$NH$_3$PbI$_3$/PMPS:B/Au and FTO/TiO$_2$/CH$_3$NH$_3$PbI$_3$/DPPS:B /Au photovoltaic devices are shown in Figure 7(a). Broad absorption spectra were obtained in the range of 400 - 780 nm. Two peak structures at 415 and 500 nm would be derived from TiO$_2$ and PbI$_2$, respectively [36] [37]. From the optical absorption spectra, energy gaps of the CH$_3$NH$_3$PbI$_3$ layers in the devices were estimated by Tauc’s formula: $(h\nu)^n = A(h\nu - E_g)$, where h, $\nu$, $\alpha$, $A$, $E_g$ and n are the Plank constant, light frequency, optical coefficient, proportional constant, energy gap, and power index which depends on the nature of the transition, respectively. In the present study, n = 2 was used for the CH$_3$NH$_3$PbI$_3$, because CH$_3$NH$_3$PbI$_3$ is a direct transition semiconductor [38]. As shown in Figure 7(b), the $E_g$ of the CH$_3$NH$_3$PbI$_3$ in the two devices were 1.59 eV, comparable with reported $E_g$ of CH$_3$NH$_3$PbI$_3$ prepared with a mixed solvent consisting of y-butyrolactone and DMF [33]. However, there was no peak
Figure 6. (a) SEM image of CH₃NH₃PbI₃ surface in FTO/TiO₂/CH₃NH₃PbI₃/DPPS:B/Au photovoltaic device. (b) EDS spectrum for FTO/TiO₂/CH₃NH₃PbI₃/DPPS:B/Au device. (c)-(f) Elemental image mapping images of (b) Pb M line, (c) I L line, (d) Si K line and (d) B K line.

Table 2. Compositions of FTO/TiO₂/CH₃NH₃PbI₃/DPPS:B/Au photovoltaic devices. BDL means below detection limit.

<table>
<thead>
<tr>
<th>Hole transport layer</th>
<th>Composition/at %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pb</td>
</tr>
<tr>
<td>PMPS:B</td>
<td>36.4</td>
</tr>
<tr>
<td>DPPS:B</td>
<td>37.1</td>
</tr>
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Figure 7. (a) Optical absorption spectra of FTO/TiO₂/CH₃NH₃PbI₃/PMPS:B/Au and FTO/TiO₂/CH₃NH₃PbI₃/DPPS:B/Au photovoltaic devices. (b) Tauc plots of FTO/TiO₂/CH₃NH₃PbI₃/PMPS:B/Au and FTO/TiO₂/CH₃NH₃PbI₃/DPPS:B/Au photovoltaic devices.
related to DPPS:B and PMPS:B layers, presumably due to their film thickness.

Figure 8(a) shows J-V characteristics of the FTO/TiO2/CH3NH3PbI3/PMPS:B/Au and FTO/TiO2/CH3NH3PbI3/DPPS:B/Au photovoltaic devices under light irradiation. The photovoltaic devices showed clear rectifying behavior with short-circuit current density (Jsc) and open circuit voltage (Voc). A Jsc of 4.56 mA cm⁻², Voc of 0.610 V, fill factor (FF) of 0.551 and conversion efficiency (η) of 1.53% were obtained for the FTO/TiO2/CH3NH3PbI3/PMPS:B/Au device. Compared with the device with PMPS:B hole transport layer, on the other hand, photovoltaic properties of the FTO/TiO2/CH3NH3PbI3/DPPS:B/Au device were improved. From the J-V characteristics of the FTO/TiO2/CH3NH3PbI3/DPPS:B/Au device shown in Figure 8(a), a Jsc of 6.96 mA cm⁻², Voc of 0.578 V, FF of 0.454 and η of 1.83% were obtained. These differences were attributed to molecular structures of the polysilanes and Si content in the hole transport layers. In fact, improvement of conversion efficiency on perovskite-based photovoltaic devices with different types of polysilane-doped spiro-OMeTAD hole transport layers were recently reported, and photovoltaic properties of the perovskite-based photovoltaic devices depended on the contents of Si [25]. The η, however, were still lower than the perovskite-based solar devices with spiro-OMeTAD, phthalocyanine, and copper thiocyanate hole transport materials [15] [16] [17] [18]. IPCE spectra of the FTO/TiO2/CH3NH3PbI3/PMPS:B/Au and FTO/TiO2/CH3NH3PbI3/DPPS:B/Au photovoltaic devices are shown in Figure 8(b). Broad IPCE spectra were obtained in the wavelength range from 300 and 800 nm, indicating that exciton and/or free charge generation occurred in the CH3NH3PbI3 layer. In addition to these results, holes in the CH3NH3PbI3 were effectively transported through the polysilane layers because intensity of the IPCE spectrum is proportional to the η, suggesting that the DPPS:B layer had a good mobility compared with the PMPS:B one. Integrated Jsc shown in Figure 8(b) agreed with the Jsc obtained from the J-V characteristics in Figure 8(a). Effective energy gaps (Eg*) can also be determined [39]. By extrapolating the linear part of the graph to meet (hv * IPCE)² = 0, the Eg* of the two devices were estimated.

Figure 8. (a) J-V curves of FTO/TiO2/CH3NH3PbI3/PMPS:B/Au and FTO/TiO2/CH3NH3PbI3/DPPS:B/Au photovoltaic devices. (b) IPCE spectra and integrated Jsc of FTO/TiO2/CH3NH3PbI3/PMPS:B/Au and FTO/TiO2/CH3NH3PbI3/DPPS:B/Au photovoltaic devices.
to be 1.57 eV (not shown), which agreed with the $E_g$ shown in Figure 7(b). These values indicate that the spectral mismatches between AM 1.5 solar simulator, IPCE measurement system and UV-VIS-NIR spectrophotometer were small.

To explain charge transport, energy band diagrams of the FTO/TiO$_2$/CH$_3$NH$_3$PbI$_3$/PMPS:B/Au and FTO/TiO$_2$/CH$_3$NH$_3$PbI$_3$/DPPS:B/Au devices are shown in Figure 9(a) and Figure 9(b), respectively. In Figure 9, previously reported values [4] [21] [40] [41] and energy gaps of PMPS:B and DPPS:B estimated from the absorption spectra shown in Figure 2 were used for the energy levels. In Figure 9(a), although the lowest unoccupied molecular orbital (LUMO) energy level of PMPS was assumed approximately −2.0 eV [41], an energy level shift of LUMO by B doping would be conceivable [42]. In Figure 9(b), it is assumed that the LUMO of DPPS is close to that of poly(di-n-butylsilane) of −1.7 eV [43] because the LUMO of DPPS has not yet experimentally and theoretically been investigated. By B doping into DPPS, energy levels of DPPS would be shifted. The charge generation occurs in the CH$_3$NH$_3$PbI$_3$ layer by light irradiation from the FTO bottom side. Electrons in the conduction band of CH$_3$NH$_3$PbI$_3$ layer are transferred to FTO anode through TiO$_2$. Simultaneously, holes in the valence band of CH$_3$NH$_3$PbI$_3$ are transported to Au cathode through the polysilanes. Compared to CH$_3$NH$_3$PbI$_3$-based photovoltaic device with PMPS:B layer, it is considered that an effective hole transport occurred from the valence band of CH$_3$NH$_3$PbI$_3$ to Au cathode through the DPPS:B in the CH$_3$NH$_3$PbI$_3$-based one, which was due to proper Si content and molecular structures of the DPPS:B. Furthermore, a heat treatment-like effect was caused for the DPPS:B layer during Au evaporation, which likely to lead to crystallization and increase in mobility of DPPS:B layer.

Finally, composition ratio of Pb and I atoms presented in Table 2 is very sensitive to photovoltaic performance. Compared with photovoltaic devices fabricated without air blow-assisted spin-coating method [25] [29] [30], the...
present CH$_3$NH$_3$PbI$_3$ layers were Pb-rich and I-poor, suggesting that the CH$_3$NH$_3$PbI$_3$ layers were $n$-type. Types of conductivity of perovskite compounds strongly depend on composition ratio of themselves. In fact, Wang et al. reported that PbI$_2$-rich CH$_3$NH$_3$PbI$_3$ behaved like an $n$-type semiconductor [44]. To improve the photovoltaic performance of perovskite-type solar cells with polysilane hole transport layers, investigation of electrical, optical and photovoltaic properties of polysilanes including $p$-type dopants should be necessary.

4. Conclusion

Perovskite-type photovoltaic devices with polysilane hole transport layers were fabricated and were investigated. As-deposited PMPS:B and DPPS:B layers were amorphous, and their optical absorption spectra showed some marked features originated from transitions. $J$-$V$ characteristics of the CH$_3$NH$_3$PbI$_3$-based photovoltaic devices with PMPS:B and DPPS:B layers exhibited different photovoltaic performance each other. Conversion efficiency of the CH$_3$NH$_3$PbI$_3$-based photovoltaic device with DPPS:B layer was slightly higher than that with PMPS:B one. These results were attributed to molecular structures of polysilanes and Si content in the polysilane hole transport layers of the present devices. In order to realize inexpensive perovskite-type solar cells with polysilane hole transport layers, further investigation of polysilanes, including electrical, optical and photovoltaic properties, and optimization of dopants and their concentration would be required.

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References


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