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Research Article

Enhancing Light-Trapping Properties of Amorphous Si Thin-Film Solar Cells Containing High-Reflective Silver Conductors Fabricated Using a Nonvacuum Process

Jun-Chin Liu,[1,2] Chen-Cheng Lin,[1] Yu-Hung Chen,[1] Chien-Liang Wu,[1] Chia-Ming Fan,[1] Yu-Ming Wang,[3] and Chung-Yuan Kung[2]

[1] *Photovoltaic Technology Division, Green Energy and Environment Research Laboratories, Industrial Technology Research Institute (ITRI), Hsinchu 31040, Taiwan*
[2] *Department of Electrical Engineering, National Chung Hsing University, Taichung 40227, Taiwan*
[3] *Micro/Nano Manufacturing Technology Department, Mechanical and Systems Research Laboratories, Industrial Technology Research Institute (ITRI), Hsinchu 31040, Taiwan*

Correspondence should be addressed to Chung-Yuan Kung; cykung@nchu.edu.tw

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We proposed a low-cost and highly reflective liquid organic sheet silver conductor using back contact reflectors in amorphous silicon (a-Si) single junction superstrate configuration thin-film solar cells produced using a nonvacuum screen printing process. A comparison of silver conductor samples with vacuum-system-sputtered silver samples indicated that the short-circuit current density (Jsc) of sheet silver conductor cells was higher than 1.25 mA/cm^2. Using external quantum efficiency measurements, the sheet silver conductor using back contact reflectors in cells was observed to effectively enhance the light-trapping ability in a long wavelength region (between 600 nm and 800 nm). Consequently, we achieved an optimal initial active area efficiency and module conversion efficiency of 9.02% and 6.55%, respectively, for the a-Si solar cells. The results indicated that the highly reflective sheet silver conductor back contact reflector layer prepared using a nonvacuum process is a suitable candidate for high-performance a-Si thin-film solar cells.

1. Introduction

The thickness of the absorbing layer of thin-film solar cells based on hydrogenated amorphous silicon (a-Si:H) is too small to absorb most of the impinging photons in a single path. To improve the short-circuit current and conversion efficiencies in an a-Si:H superstrate configuration of thin-film solar cells, an optimal light-trapping scheme is necessary. Recently, the design of the front contact layer light trapping in conventional a-Si solar cells was primarily derived from the textured transparent conductive oxide (TCO) layer on the glass substrate using an etching process [1–4]. The mechanisms produce a statistical surface morphology of various lateral sizes, heights, and shapes. The textures provide light scattering, which extends the light path in an a-Si layer at various angles. However, silicon thin-film growth is highly sensitive to substrate surface morphology because of the V_{oc} drop. Based on TEM images, white stripe-like defective regions were generated in the intrinsic a-Si layer deposited on highly textured SnO_2 transparent electrodes [5]. Moreover, the employment of highly textured ZnO:B in argon plasma etching processes provides the advantage of improving light absorption and enhancing Jsc. By contrast, poor FF and V_{oc} were observed [6]. Compared with front contact light trapping, other technological approaches used to produce optimal textured substrates result in markedly different feature sizes and shapes, and a control is not simple. Back-metal contact is relatively simple to fabricate, and light scattering at the back interface also enhances light trapping primarily because of the textured back reflectors (BRs) [7].

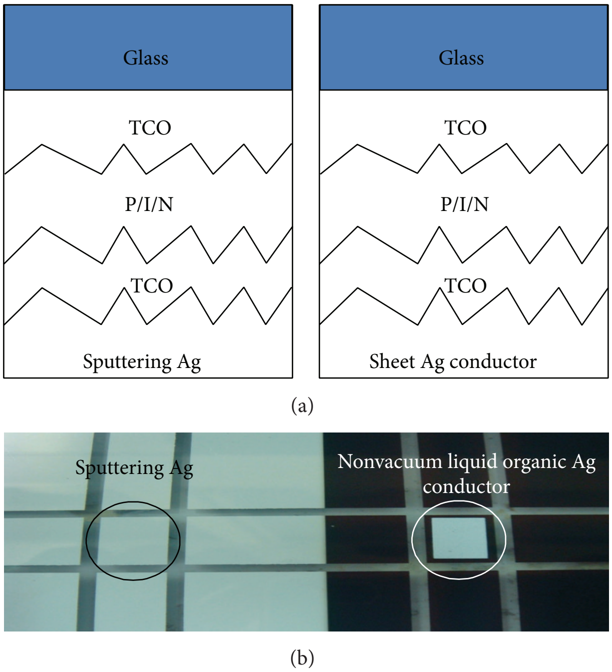


Figure 1: (a) Schematic sketch of two a-Si:H p-i-n solar cell structures for BRs study; (b) real samples fabricated by sputtering and nonvacuum screen printing process, respectively.

The conventional Si thin-film solar cell technology depends on textured metal-based back reflectors, which typically consist of a silver layer deposited on a thin TCO layer, such as ZnO [7]. Although silver reflectors exhibit excellent electrical and optical reflectivity properties, they still require a high manufacturing cost when using the sputtering vacuum system. Thus, from an industrial viewpoint, the silver reflector layer should be manufactured as inexpensively as possible without compromising adequate light trapping. We proposed an alternative approach in this study. A low-cost and highly reflective liquid organic silver conductor was developed as a back-metal reflector layer using a nonvacuum screen printing process for a-Si single junction p-i-n solar cells. We effectively enhanced the short-circuit current density in quantum efficiencies in the infrared wavelength region and also reported on the improved performance of large a-Si thin-film solar cell modules.

2. Experimental

Amorphous Si (a-Si) single-junction p-i-n solar cells were deposited using a 40 MHz very high-frequency plasma-enhanced chemical vapor deposition (VHF-PECVD) cluster system. Intrinsic a-Si:H thin films were grown using SiH_4/H_2 gas mixtures that were approximately 350 nm thick at 200°C. The optical band gap of the intrinsic a-Si:H thin films was 1.75 eV, determined using the conventional Tauc's plot method. The photosensitivity characteristics of the a-Si:H thin films were approximately 5 orders of magnitude [8]. Boron-doped amorphous silicon oxide (p-a-SiO:H) layers were deposited using $B_2H_6/SiH_4/N_2O/H_2$ gas mixtures. The p-layer thickness was approximately 10 nm. Phosphorus-doped microcrystalline silicon n-layers (n-μc-Si:H) were then deposited in a mixed atmosphere of $PH_3/SiH_4/H_2$ gases to a thickness of approximately 9 nm. The final device structure was an Asahi glass (U-type/SnO_2:F) substrate/p-a-SiO:H/i-a-Si:H/n-μc-Si:H/ZnO/Ag. In this study, we employed the vacuum sputtering silver process and the nonvacuum liquid organic silver conductor using a screen printing process to investigate various silver BRs of light-trapping properties in the cells. A schematic view of two types of a-Si:H solar cell structures is shown in Figure 1. We developed a liquid organic silver conductor chemical composition including commercially available silver flake powder, ethyl cellulose ethoce, and an α-terpineol solvent. The mixtures were mixed using a high-speed mixer for 3 min. Subsequently, uniform pastes were formed using triple roller grinding. The silver conductor consisted of 70% silver powder. Finally, the liquid organic silver conductor that served as a BR layer in a-Si devices was baked on a hot plate at 80°C. The thickness is approximately 2 μm and sheet resistivity is 5.4 mΩ/square. The silver-sputtering BR layer was made using an RF magnetron sputtering vacuum system. The deposition conditions were 300 W at sputter gas pressures of 5 mTorr in an Argon gas atmosphere. The thickness is approximately 200 nm and sheet resistivity is 3.2 mΩ/square. The current density-voltage (J-V) test cells had an active area of 4.0 cm^2. The performance of the solar cells was then characterized using J-V measurements under standard AM1.5 (100 mW/cm^2) illumination at 25°C. The external quantum efficiency (EQE) of the solar cells was measured at zero bias voltage to determine their spectral responses at various wavelengths. The optical properties of the BRs were characterized using the PerkinElmer LAMBDA 750S UV/Vis/NIR spectrophotometer to measure the total reflection spectra. Figure 2 shows the a-Si module solar cell fabrication flowchart. Figure 2(a) shows the typical interconnected scheme drawing of an a-Si:H module cell in a superstrate configuration. The interconnection of cells into a module was achieved using the following three steps of laser scribing: TCO cutting, a-Si layer ablation, and back-contact removal, named P1, P2, and P3, respectively. The incident light passed through a glass substrate on which a TCO electrode was formed and was integrated using laser-scribe processing, as shown in Figure 2(b). Subsequently, the liquid organic silver conductor film was employed as the BRs in a-Si:H module solar cells using a nonvacuum screen printing process. Step P3 of the laser scribe process could be omitted, which consequently reduced the back-contact manufacturing process.

3. Results and Discussion

Figure 3 shows the SEM photographs of the liquid organic sheet silver conductor film that was successfully deposited onto a glass substrate surface. The diameter of the sheet silver ranged between 2 and 12 μm. The sheet silver conductor film was nearly interconnected adequately during the nonvacuum screen printing process. Such a dense interconnected sheet

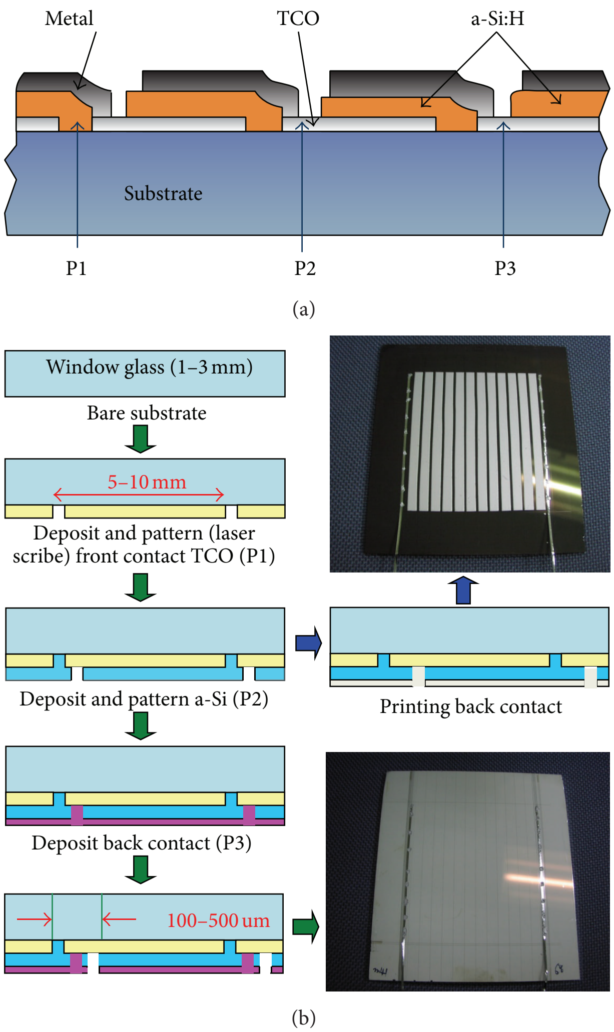


FIGURE 2: (a) Cross-sectional structure of the a-Si:H module; (b) schematic view of the P1, P2, P3, and screen printing back contact process.

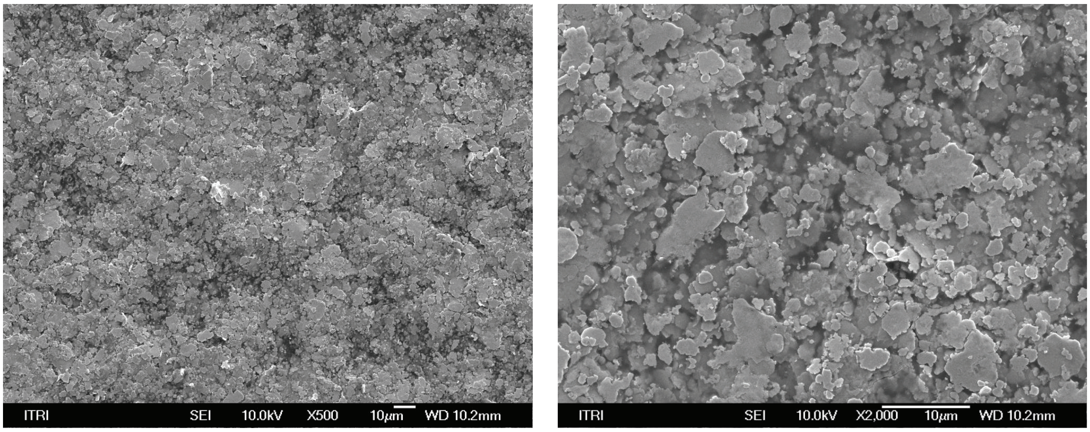
structure may increase light-trapping efficiency by increasing light reflectance and, furthermore, it also maintains excellent contact conductivity. Compared with the sputtering silver process, the nonvacuum screen printing process can easily achieve large-scale fabrication and low fabrication costs that could result in rapid commercial adoption.

Figure 4 shows the light reflectance measurement of sputtering silver and liquid organic sheet silver conductor films, produced using a nonvacuum screen printing process and deposited on a textured Asahi glass substrate. The average total reflectance obtained from the screen printing process (approximately 51%) was higher than that obtained from the sputtering process (approximately 39%). The average total reflectance of the sheet silver conductor film sample was higher by nearly 28% in the visible light region, indicating that the sheet silver BR film exhibited superior scattering properties, which was primarily caused by the absence of a surface plasmon absorption effect, compared with the high absorption loss and low reflectivity of the sputtering silver BR sample [9]. In addition, regarding a-Si cells, when the incident light passed through the glass and TCO and arrived at the textured interface containing the silicon, most of the light was absorbed; however, the light in the near-infrared (NIR) region was not completely absorbed in the silicon layer and arrived at the back contact reflector layer. Thus, excellent reflectivity is crucial in the NIR region. A rough metal interface is generally known to exhibit a lower total reflectance than that of a smooth metal surface [10]. As observed in Figure 4, the sheet silver BR sample evidently exhibited a higher IR reflectivity than the silver-sputtering BR sample did, suggesting that the proposed silver conductor was smooth. This high reflectivity is advantageous and serves to back-reflect the long wavelength light, increase the optical path of absorbed light in the a-Si layer, and improve device performance.

The J-V characteristics of a-Si:H p-i-n solar cells under illumination and subjected to various BR processes are shown in Figure 5. A sheet silver conductor BR film prepared using a nonvacuum screen printing process was observed to yield superior cell performance. We achieved an initial active-area efficiency of 9.02%. Compared with the sputtering silver BR sample, an evident increase in Jsc of 1.25 mA/cm^2 was observed when the sheet silver was introduced as a BR sample. This indicates that the extent of light reflectance, which depends on the sheet silver conductor, considerably influenced the optical properties of the a-Si solar cells. The tendency of the experimental results was consistent with the measured data in Figure 4.

To confirm the excellent cell performance produced by the sheet silver conductor BRs, we measured the EQE curves under a zero bias condition. Generally, light scattering at the back contact plays a dominant role in enhancing the spectral response at a wavelength longer than 600 nm. Figure 6 shows the EQE spectra response for a-Si:H p-i-n solar cells using several BR processes. The spectral response of the sheet silver BR cells in the red spectral range increased to a level greater than that of the sputtering silver cells (22% to 34% at 700 nm). The observations indicated that the sheet silver conductor improved light trapping at wavelengths longer than 600 nm. In contrast to the sheet silver conductor cells, the sputtering silver cells exhibited a lower reflectance, which may be related to the poor optical utilization rate that was accountable for the lower Jsc. This result is consistent with the expected results derived from the reflectance and J-V measurements shown in Figures 4 and 5.

Finally, we fabricated a-Si p-i-n single junction superstrate-type modules by using two types of BR processes. The cell recipe and scribing process enabled a 225 cm^2 a-Si module to be achieved. The modules comprised 12 cells with 8 cm^2 areas; therefore, the calculated efficiency value refers to an active area of 96 cm^2. Table 1 lists thephotovoltaic parameters of the a-Si solar cells and module performance. Compared with the sputtering silver module, the sheet silver conductor module exhibited superior short-circuit current density (Jsc = 12.86 mA/cm^2) and conversion efficiency



(a) (b)

FIGURE 3: The SEM photographs of nonvacuum liquid organic sheet silver conductor film deposited on glass substrate surface by screen printing process. Zoom-in (a) 500 times and (b) 2000 times.

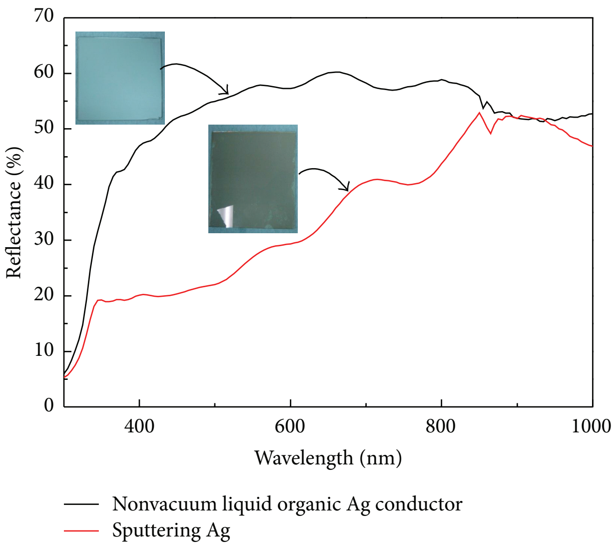


FIGURE 4: Light reflectance spectra of sputtering Ag and nonvacuum liquid organic sheet silver conductor film by screen printing process deposited on textured Asahi glass substrate, respectively.

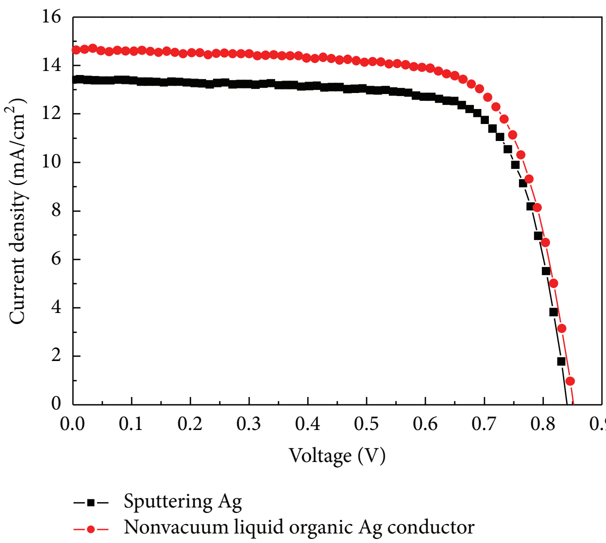


FIGURE 5: J-V characteristics for a-Si:H p-i-n solar cells under illumination with different back reflectors process.

TABLE 1: Performance of a-Si:H p-i-n solar cells with different back reflectors.

	V_{oc} (V)	Jsc (mA/cm^2)	F.F. (%)	η (%)
Sputtering Ag	0.841	13.41	73.42	8.28
Nonvacuum liquid organic sheet Ag conductor	0.852	14.66	72.23	9.02
Sputtering Ag module	0.85	11.1	63.4	5.98
Nonvacuum liquid organic sheet Ag conductor module	0.85	12.86	60.0	6.55

(η = 6.55%), indicating substantially improved light-trapping properties.

4. Conclusion

In this study, we determined that the proposed highly reflective sheet silver conductor back contact reflector layer, fabricated using a nonvacuum process, is a suitable candidate for high-performance a-Si thin-film solar cells. The light reflectance, J-V, and EQE measurement results indicated that the sheet silver conductor BR devices can yield excellent light-trapping properties. By contrast, sputtering silver BR devices exhibited poor photovoltaic performance, because the rough metal interface exhibited a low total reflectance over the entire wavelength. Using optimal sheet silver conductor BRs, we achieved the optimal initial active area efficiency of 9.02% and a module efficiency of 6.55%. The key reason for this

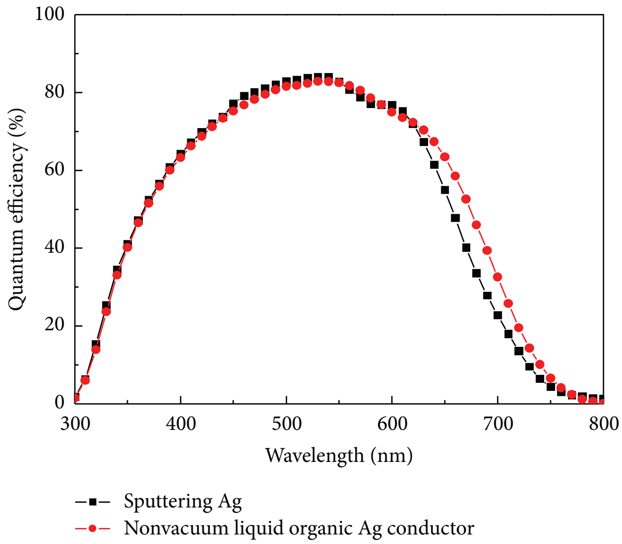


Figure 6: EQE spectra response for a-Si:H p-i-n solar cells with different back reflectors process.

superiority was the effectively improved short-circuit current density and the enhanced BR light-trapping capability.

Conflict of Interests

The authors declare that they have no conflict of interests regarding the publication of this paper.

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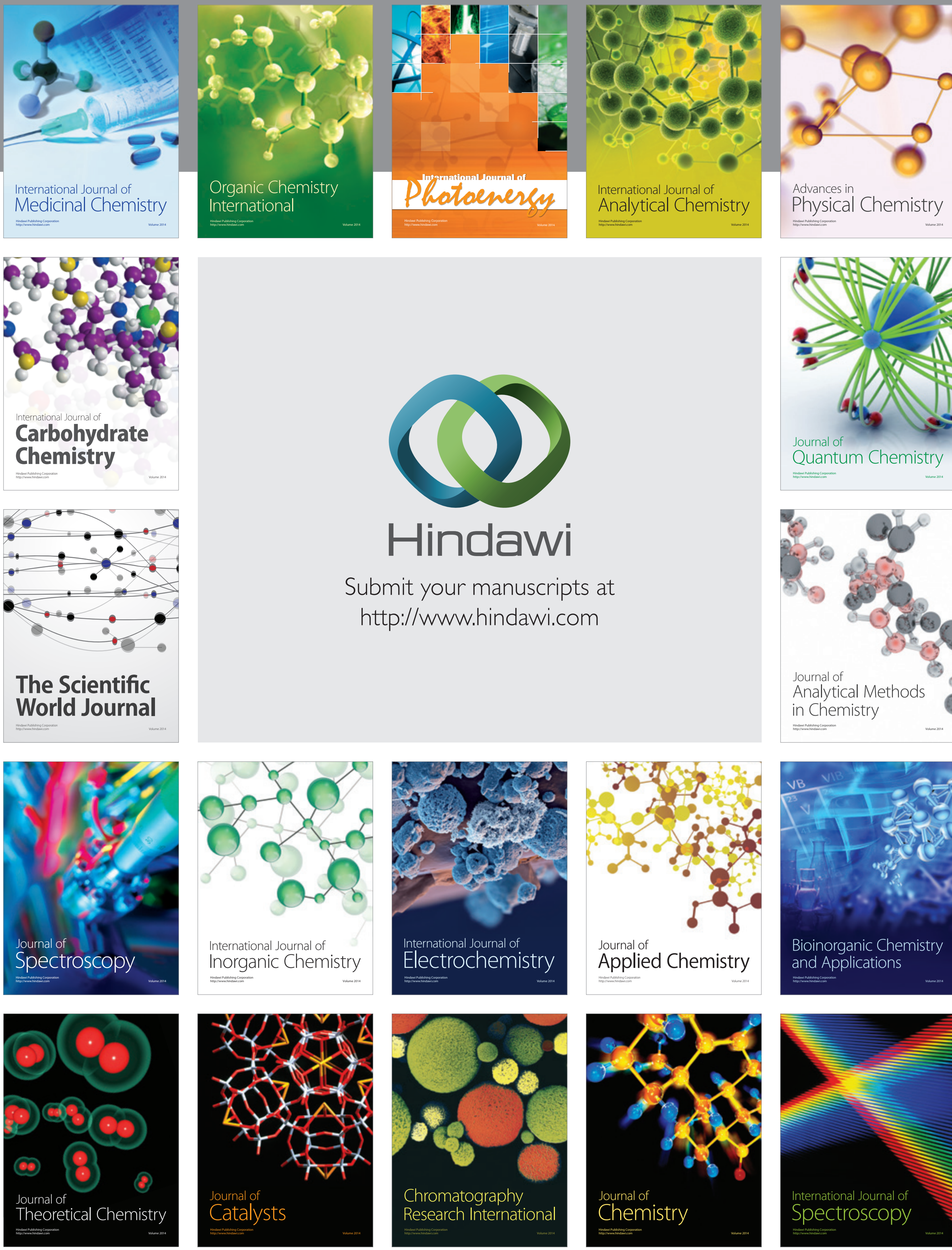
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