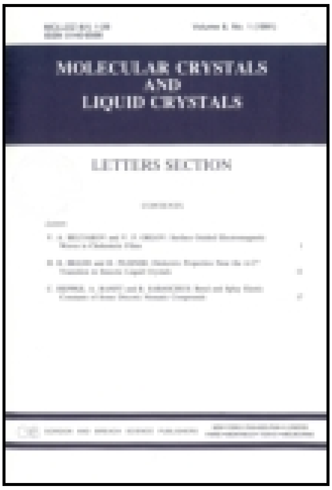

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Effects of RF Power and Substrate Temperature on the Performance of Thin-Film Silicon Solar Cells

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This article shows the characteristics of pin-type solar cells with different radio frequency (RF) power and substrate temperature (T_s). All films of amorphous materials were deposited by 13.56 MHz plasma enhanced chemical vapor deposition (PECVD) method using a mixture of silane (SiH_4) and hydrogen (H_2). The SiH_4 gas was used as a gas source and the doping process was done by gas admixture of 3% diborane (B_2H_6) diluted in hydrogen (H_2) and 1% phosphine (PH_3) diluted in H_2 for p- and n-layer, respectively. The effects of deposited parameters on the characteristics of a-Si:H films have been investigated by field emission scanning electron microscope (FE-SEM), dark- and photo-conductivity (σ_d and σ_{ph}) measurement and ultraviolet-visible-near infrared (UV-VIS-NIR) spectrophotometer, respectively. The results showed that the deposition rate of a-Si:H films increased with increasing of RF power and T_s. The optical band gap (E_{opt}) of a-Si:H films was increased with increasing of RF power from 20–60 Watt, and slightly decreased at RF power of 60–100 Watt. The various values of open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}), and conversion efficiency were measured by the solar simulator. It was found that a-Si:H films deposited at RF power of 60 Watt and T_s of 200°C are better suited for thin-film silicon solar cell application.

Keywords a-Si:H; pin-type solar cell; optical properties; electrical properties; PECVD

Introduction

Hydrogenated amorphous silicon (a-Si:H) has been widely studied as a basic material for thin-film transistors (TFTs) [1, 2, 3], light emitting diodes (LEDs), thin-film solar cells [4, 5], and many other optoelectronic devices [6]. Advantages of the a-Si:H based solar cell over a crystalline silicon solar cell include high optical absorption in the range from 370 to 780 nm [7, 8, 9], low temperature (< 300°C) fabrication, feasibility of large area solar cell (larger than 1 m^2), and rather simple solar cell processing. However, the cell performances are still low despite of many trials of research on a-Si:H solar cell. In generally, the characteristics of a-Si:H films are determined by localized defect states arising from

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Table 1. Deposition conditions of a-Si:H films

Deposition conditions	Parameters
Gas flow rate (sccm):	
SiH_4	115
H_2	200
RF frequency (MHz)	13.56
RF power (W)	20–100
Reaction pressure (mTorr)	750
Substrate temperature (°C)	200, 250
Thickness (nm)	200

structural disorder such as dangling bonds in the band gap. The incorporation of hydrogen during the deposition process greatly reduces the defect density, then hydrogen atoms bond with most of the silicon dangling bonds in the band gap. Despite that, the density of defect states still exists in the a-Si:H films. It affects the properties of charge carrier transport and facilitates the recombination in the band gap, resulting in poor collection of generated carriers in cell [10]. In order to achieve a higher conversion efficiency of a-Si:H based solar cells, a higher quality of a-Si:H material is required. Also, it is necessary to obtain more detailed information about the influence of deposition conditions (e.g. radio frequency power, working pressure, and substrate temperature).

In this work, we have investigated the characteristics of pin-type a-Si:H solar cells with different radio frequency (RF) power and substrate temperature (T_s). The optimum deposition condition of each layer was determined by evaluating the cell performance parameters. All films of amorphous materials were deposited by plasma enhanced chemical vapor deposition (PECVD) method. The cell characteristics were measured with solar simulator under standard AM 1.5G conditions.

Experimental Details

All films of amorphous materials were deposited by 13.56 MHz PECVD using 10% silane (SiH_4) diluted in helium (He) at a flow rate of 115 sccm (standard cubic centimeter per minute) in single chamber. The SiH_4 gas was used as a gas source and the doping process was done by gas admixture of 3% diborane (B_2H_6) diluted in hydrogen (H_2) and 1% phosphine (PH_3) diluted in H_2 for p- and n-layer, respectively. The deposition conditions were: working pressure 750 mTorr, T_s 175, 200, 250, and 300°C, respectively. The deposition rate was controlled by varying the RF power from 20 to 100 Watt. More detailed information about the deposition conditions of a-Si:H films and pin-type solar cells can be found in Table 1 and Table 2. The pin-type solar cells were fabricated a simple structure of glass/ITO (Indium Tin Oxide)/p-a-Si:H/i-a-Si:H/n-a-Si:H/aluminum (Al) with different RE power and T_s. The Al to deposit back electrode was used by the thermal evaporator. The thicknesses of p-, i-, and n-layers were 18, 200, and 60 nm, respectively. The thickness of a-Si:H films was estimated by FE-SEM observation. The optical properties (absorption coefficient and optical band gap) of the a-Si:H films were measured with UV-VIS-NIR spectrophotometer. and The electrical properties (dark- and photo-conductivity, σ_d and σ_{ph}) of the a-Si:H films were then obtained by current-voltage (I-V) measurement using two point probe (coplanar) method. The open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}), and fill factor

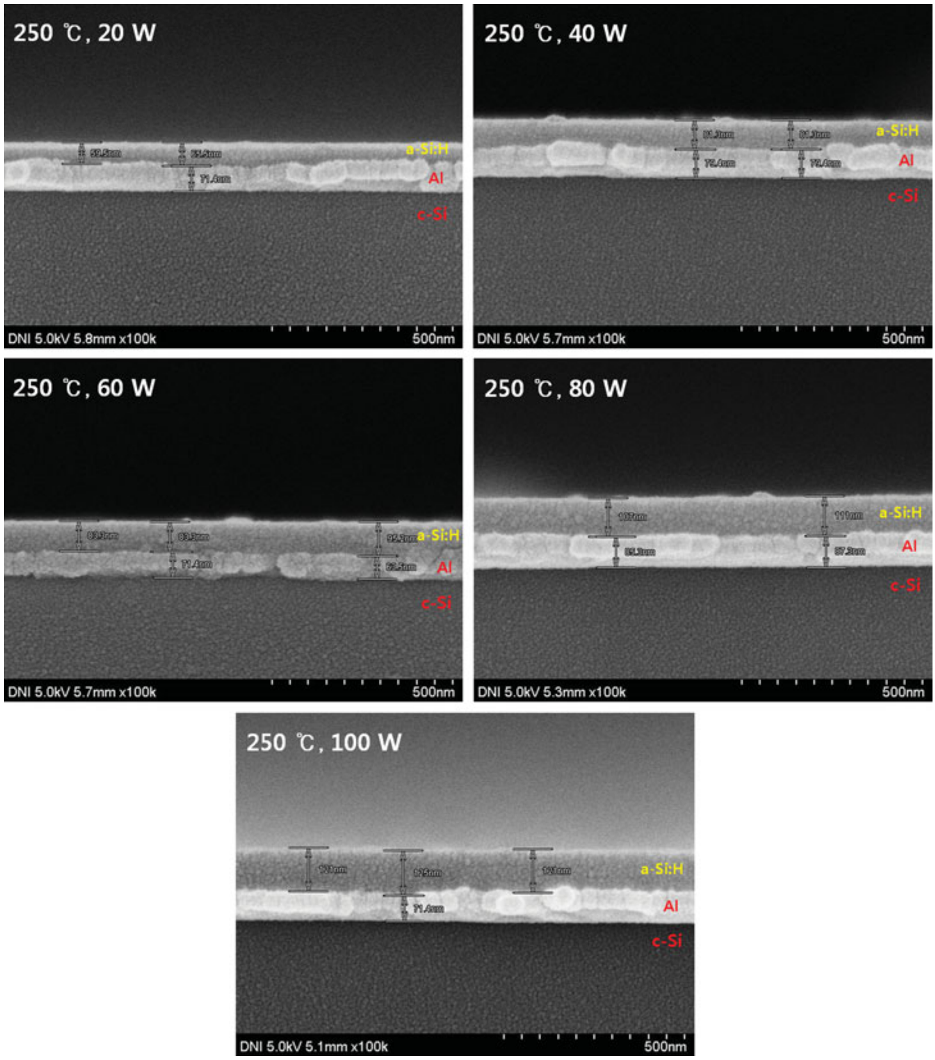

Figure 1. SEM images of a-Si:H films with different RF power.

Table 2. Deposition conditions of pin-type a-Si:H solar cells

	p-a-Si:H	i-a-Si:H	n-a-Si:H
Gas	SiH_4/B_2H_6	SiH_4/H_2	SiH_4/PH_3
Gas flow rate (sccm)	115/5.4	115/200	115/15.4
RF frequency (MHz)	13.56	13.56	13.56
RF power (W)	20–100	20–100	20–100
Reaction pressure (mTorr)	750	750	750
Substrate temperature (°C)	175–300	175–300	175–300
Thickness (nm)	18	200	60

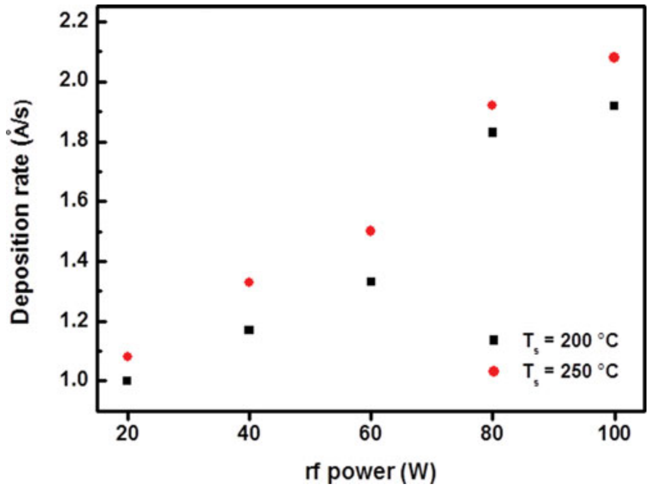

Figure 2. Deposition rate of a-Si:H films deposited at different T_s as a function of RF power.

(FF) of the solar cells were obtained from the J-V measurements performed under the solar simulator in standard test conditions (25°C, AM 1.5G spectrum, and 100 mW/cm^2).

Results and Discussion

Comparison of a-Si:H Films in Different Conditions for RF Power and T_s

Figure 1 shows the SEM images of cross section of a-Si:H films deposited with different RF power. The deposition conditions were: working pressure 750 mTorr, T_s 250°C, and deposition time 10 min, respectively. The deposition rate was controlled by varying the RF power from 20 to 100 Watt. Figure 2 shows the deposition rate of a-Si:H films deposited at different T_s as a function of RF power. The RF power and T_s have a strong correlation with

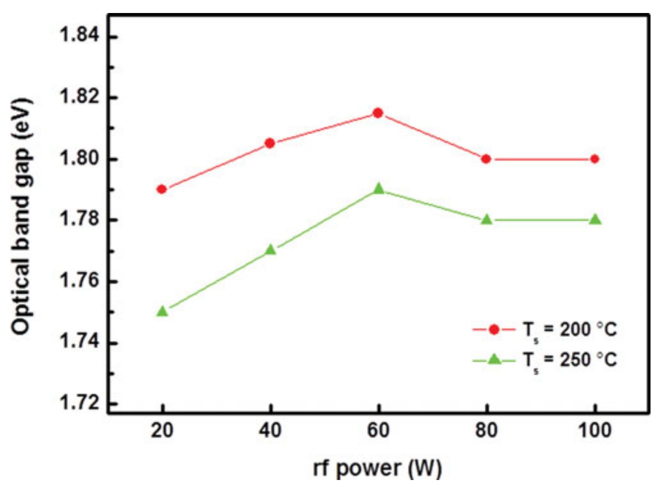

Figure 3. Optical band gap (E_{opt}) of a-Si:H films deposited at different T_s as a function of RF power.

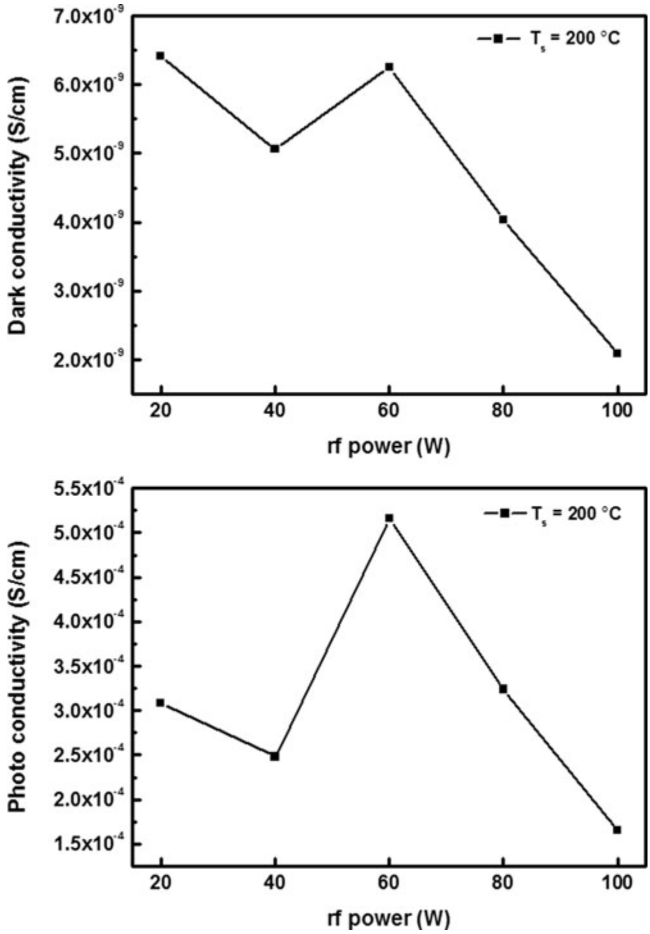

Figure 4. Dark- and photo-conductivity (σ_d and σ_{ph}) of a-Si:H films as a function of RF power.

the reactivity of adsorbed radicals on the growing surface. We confirmed that the deposition rate of a-Si:H films increased with increasing of RF power and T_s.

The optical and electrical properties of a-Si:H films were compared with different RF power and T_s. Figure 3 shows the optical band gap (E_{opt}) of a-Si:H films deposited at different T_s as a function of RF power. The absorption coefficient (α) and E_{opt} was calculated according to the equations (1) and (2).

$$\alpha = -\frac{1}{d} \ln \frac{T(\lambda)}{(1 - R(\lambda))^2} \quad (1)$$

where d is the thickness of the film, R (λ) and T (λ) denote the reflection and the transmission, respectively.

$$(\alpha h\nu)^{1/2} = B(h\nu - E_{opt}) \quad (2)$$

where E_{opt} is the optical band gap and B is proportional factor. The E_{opt} was determined using Tauc's plot method from hν versus $(\alpha h\nu)^{1/2}$, where hν is the photon energy [11].

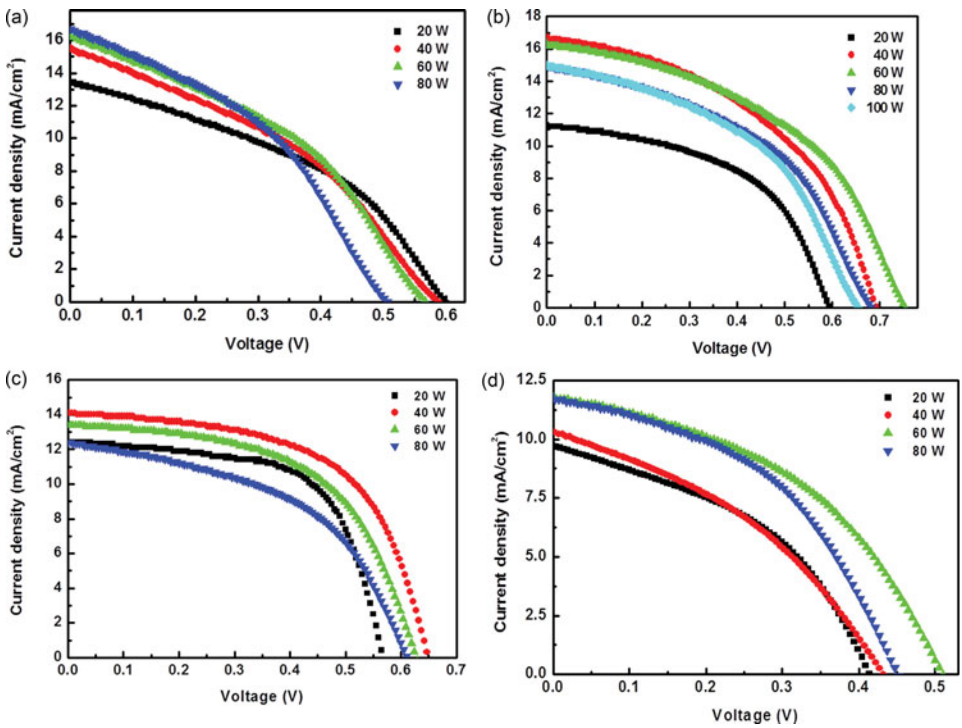

Figure 5. Photocurrent density-voltage (J-V) characteristics of pin-type a-Si:H solar cells with different RF power and T_s for (a) 175°C, (b) 200°C, (c) 250°C, and (d) 300°C.

We confirmed that the E_{opt} of a-Si:H films was decreased with increasing T_s from 200 to 250°C. Also, it was increased with increasing RF power from 20 to 60 Watt, and slightly decreased at RF power from 60 to 100 Watt. The E_{opt} of a-Si:H films does not have a linear relation to RF power, because of the strongly depending on the composition of Si and H atoms.

Figure 4 shows the electrical properties (dark- and photo-conductivity, σ_d and σ_{ph}) of the a-Si:H films as a function of the RF power. At T_s of 200°C, the σ_d and σ_{ph} were decreased with increasing RF power from 60 to 100 Watt. The decrease in electrical properties is probably due to the increases of defect density. It is well known that the RF power controls the characteristic of a-Si:H films, especially the hydrogen content and structural disorder [12]. It is an important factor which impact the films quality of a-Si:H. From the fig. 4, we confirmed that the a-Si:H films quality can be improved by controlling the deposition conditions. For optimized a-Si:H films having RF power of 60 Watt, photo-conductivity is slightly high.

Comparison of Solar Cell Performances in Different Conditions for RF Power and T_s

To obtain the optimum p-, i-, and n-layer, the solar cells of pin-type were fabricated with different deposition conditions. Figure 5(a)–(d) show the J-V characteristics on pin-type a-Si:H solar cells with different RF power and T_s under AM 1.5 (100 mW/cm^2) illumination. The J-V characteristics were measured using a source meter (Keithley 2400) and a solar simulator with a xenon arc lamp. From these results, we have found that the

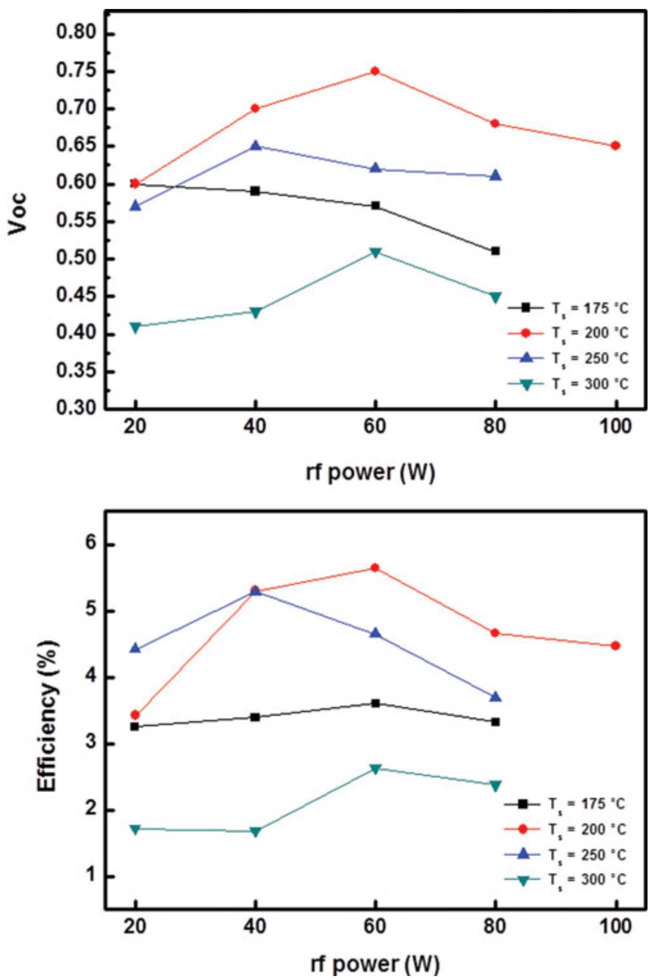

Figure 6. Correlation between the open-circuit voltage (V_{oc}) and the conversion efficiency (E_{ff}) in pin-type a-Si:H solar cells with different RF power and T_s.

optimum RF power and T_s which resulted in a good performance cell were 200°C and 60 Watt, respectively. A typical cell performances are $V_{oc} = 0.75$ V, $J_{sc} = 16.25$ mA/cm^2, FF = 0.46, and $E_{ff} = 5.64$ %.

Figure 6 shows the correlation between the V_{oc} and the E_{ff} in pin-type a-Si:H solar cells with different RF power and T_s. The graphs show a very similar shape. At T_s of 175 and 300°C, the solar cells are shown very poor performances. Thus, these deposition conditions were proven as not useful for improvement of cell performance. From these results, we confirmed that the V_{oc} strongly depend upon the deposition conditions.

To investigate these effects on solar cell performance, we made a-Si:H films of different RF power. and confirmed the opto-electronic properties of these films. Figure 7 shows the photo-sensitivity (σ_{ph}/σ_d) of a-Si:H films as a function of RF power. The results showed that the photo-sensitivity was increased with increasing RF power from 20 to 60 Watt, and slightly decreased at RF power from 60 to 100 Watt. At RF power of 60 Watt, the a-Si:H

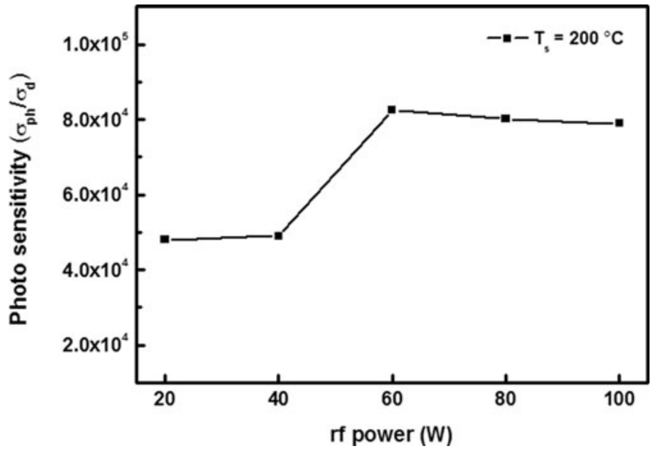

Figure 7. Photo-sensitivity (σ_{ph}/σ_d) of a-Si:H films as a function of RF power.

films have good photo-sensitivity (8.3×10^4). Thus, this deposition condition was proven as useful for improvement of cell performance.

Conclusions

In this work, we have investigated the characteristics of a-Si:H films and pin-type a-Si:H solar cells deposited by the PECVD method with different RF power and T_s. and studied their optical and electrical properties using FE-SEM, UV-VIS-NIR spectrophotometer, and conductivity measurement. Also, we have shown that reasonable quality a-Si:H films and pin-type solar cells can be made by carefully controlling the deposition conditions for RF power and T_s. To confirm performance of fabricated solar cells, compared the characteristics in different deposition conditions. From these results, we confirmed that the solar cell has the highest conversion efficiency of 5.64 % ($V_{oc} = 0.75$ V, $J_{sc} = 16.25$ mA/cm^2, FF = 0.46) when the RF power and T_s were 60 Watt and 200°C, respectively. Moreover, we successfully obtained a good quality films of a-Si:H with photo-sensitivity of 8.3×10^4 under the same deposition conditions.

Funding

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