20.1%-efficient industrial-type PERC solar cells applying ICP AlO_x as rear passivation layer

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ABSTRACT

The passivated emitter and rear cell (PERC) is considered to be the next generation of industrial-type screen-printed silicon solar cell. However, only a few deposition methods currently exist for rear passivation layers which meet both the high-throughput and low-cost requirements of the PV industry while demonstrating high-quality surface passivation properties. This paper presents an evaluation and the optimization of a novel deposition technique for AlO_x passivation layers, applying an inductively coupled plasma (ICP) plasma-enhanced chemical vapour deposition (PECVD) process. High deposition rates of up to 5nm/s, as well as excellent surface recombination velocities below 10cm/s after firing, are possible using this ICP AlO_x deposition process. When applied to PERC solar cells the ICP AlO_x layer is capped with a PECVD SiN_y layer. Independently confirmed conversion efficiencies of up to 20.1% are achieved for large-area 15.6cm × 15.6cm PERC solar cells with screen-printed metal contacts and ICP AlO_x/SiN_y rear side passivation on standard boron-doped Czochralski-grown silicon wafers. The internal quantum efficiency (IQE) reveals an effective rear surface recombination velocity S_{rear} of 110±30cm/s and an internal rear reflectance R_b of 91±1%, which demonstrates the excellent rear surface passivation of the ICP AlO_x/SiN_y layer stack. Currently, the ICP AlO_x deposition process is being transferred from the ISFH laboratory-type tool to the Singular production tool of Singulus Technologies in order to commercialize this novel deposition process during 2012.

Introduction

The passivated emitter and rear cell (PERC) is a very promising candidate for next-generation industrial-type screen-printed silicon solar cells. The International Technology Roadmap for Photovoltaics (ITRPV) forecasts the introduction of rear-passivated cells into volume production within the next two years [1]. Numerical simulations using typical solar cell parameters indicate that the conversion efficiency of screen-printed PERC cells is up to 1.5% (absolute) higher than screen-printed solar cells with full-area aluminium back surface field (Al-BSF) owing to the reduced rear surface recombination velocity S_{rear} and an increased rear surface reflectance R_b [2,3]. Excellent conversion efficiencies above 20.0%, with record values of up to 20.2%, have been demonstrated by several companies and research institutes for large-area p-type PERC solar cells with screen-printed metal contacts [4,5,6,7]. Several production-type tools for the deposition of rear passivation layers are already available on the market [8,9] or under development [10,11]. In particular, rear passivation layers consisting of aluminium oxide (AlO_x) have attracted considerable attention because of their excellent surface passivation properties. Effective surface recombination velocities below 10cm/s have been demonstrated [12] for Al_2O_3 layers deposited by atomic layer deposition (ALD) after a high-temperature firing step which is typically carried out for screen-printed metal contacts.

> "In addition to excellent electrical properties, it is important that the AlO_x deposition process achieve high deposition rates."

However, in addition to excellent electrical properties, it is important that the AlO_x deposition process achieve high deposition rates and hence a high throughput, which enables a low cost of ownership. Plasma-enhanced chemical vapour deposition (PECVD) processes applying an inductively coupled plasma (ICP) form a high-density plasma (HDP), yielding electron densities of around $1\times10^{12}cm^{-3}$ [13], and hence allow high deposition rates of up to several nanometres per second [14]. ICP PECVD processes have been extensively investigated for the deposition of dielectric insulation and encapsulation layers consisting of SiO_x [15,16] or SiN_x [16,17,18]. The focus at that time was on applications in microelectronic manufacturing, such as a final passivation layer or a diffusion barrier. One important feature of the ICP process is that the plasma density can be varied independently of the ion energy, which is typically lower than 30eV. Hence, an independent optimization of the deposition rate versus the reduction of surface damage of the silicon wafer is possible. In recent years, Singulus Technologies has commercialized the ICP process for the deposition of SiN_x anti-reflective layers of silicon solar cells using their Singular tool platform [14].

This paper presents an investigation of the application of the ICP process, to our knowledge for the first time, to the deposition of AlO_x layers. The ICP AlO_x layers are deposited using a laboratory-type tool at ISFH. The surface passivation properties of the resulting ICP AlO_x layers are analyzed, and the SiN_y capping layer deposition is optimized in order to improve the surface passivation quality after firing. For rear passivation, ICP AlO_x/SiN_y layer stacks are applied to large-area PERC solar cells with screen-printed metal contacts, resulting in excellent conversion efficiencies of up to 20.1%. Moreover, the electrical and optical properties of the ICP AlO_x/SiN_y layers are analyzed by measuring and modelling the internal quantum efficiency (IQE) and the reflectance of the resulting PERC solar cells.

AlO_x deposition using an ICP process

The ICP AlO_x layers are deposited in a laboratory-type cluster tool (Von Ardenne CS 400 P) at ISFH; the tool consists of a load lock chamber, a transfer chamber and several PECVD deposition chambers, including the ICP AlO_x

chamber as shown in the photograph in Fig. 1(a). A schematic drawing of the ICP AlO_x deposition chamber is given in Fig. 1(b). A coil outside the vacuum chamber inductively excites the plasma using a high-frequency generator set at a frequency of 13.56MHz. Trimethylaluminium (TMAl) is used as the precursor gas, and oxygen (O_2) as a reactive gas. The silicon wafer is transported on a carrier and electrically heated during the AlO_x deposition.

Depending on the process parameters, high static deposition rates of up to 5nm/s are obtained while maintaining low ion energies below 30eV. The thickness of the resulting ICP AlO_x layers is varied by adjusting the time of the deposition process. Afterwards, the ICP AlO_x passivation layers are covered with a PECVD SiN_y capping layer (SiNA/Roth & Rau or Singular/Singulus) in order to improve the firing stability and the optical reflectivity when applied to PERC solar cells.

Surface passivation properties of ICP AlO_x layers

In order to determine the surface passivation properties, ICP AlO_x layers capped with a PECVD SiN_y layer (SiNA/Roth & Rau) are deposited on both sides of p-type 1.4Ωcm float zone (FZ) wafers, and a typical firing process is carried out in a conveyor belt furnace with peak temperatures of 910°C. The minority charge carrier lifetime is then measured using the quasi-steady-state photoconductance (QSSPC) technique at a carrier density of $1\times10^{15}cm^{-3}$. Using the measured lifetime τ_{eff}, the maximum surface recombination velocity S_{max} (attributing the whole recombination to the wafer surface) can be calculated from the equation $S_{max} = W/(2 \times \tau_{eff})$, where W is the mean wafer thickness.

> "QSSPC measurements reveal excellent effective lifetimes of up to 2ms."

The QSSPC measurements reveal excellent effective lifetimes of up to 2ms, corresponding to surface recombination velocities (SRVs) S_{max} below 10cm/s for ICP AlO_x/PECVD SiN_y layer stacks after firing, as shown in Fig. 2. The error bars in Fig. 2 refer to the minimum and maximum values of the effective lifetimes measured at different positions on the same wafer, revealing a good homogeneity of the surface passivation across the wafer. A moderate dependence of the SRV on the AlO_x layer thickness can be seen, with a minimum value of 7.5±1.5cm/s at an AlO_x thickness of 15nm.

The next step is to evaluate a SiN_y capping layer applied by the Singular tool

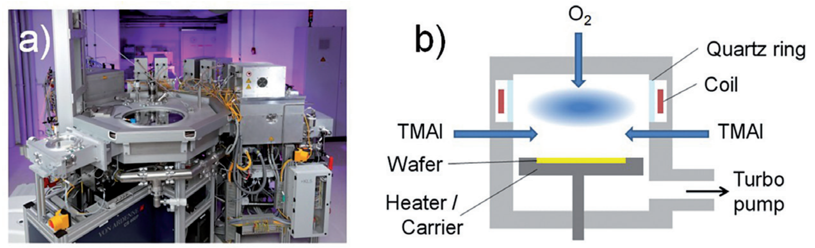

Figure 1. (a) The laboratory-type cluster tool (Von Ardenne CS 400 P), consisting of a load lock chamber, a transfer chamber and several process chambers, including the ICP AlO_x deposition chamber. (b) Schematic of the ICP AlO_x deposition chamber – plasma is inductively excited with a coil outside the vacuum chamber using TMAl and O_2 as process gases, and the wafer is transported on a carrier and heated during deposition.

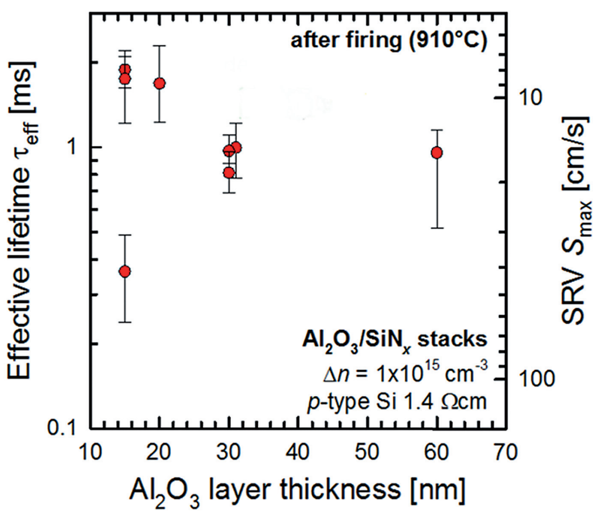

Figure 2. Effective carrier lifetimes and corresponding surface recombination velocities (SRVs) as a function of the ICP AlO_x layer thickness, measured for 1.4Ωcm float zone (FZ) wafers. The results indicate lifetimes of up to 2ms and SRVs below 10cm/s for ICP AlO_x layers covered with a PECVD SiN_y layer (SiNA/Roth & Rau) after firing.

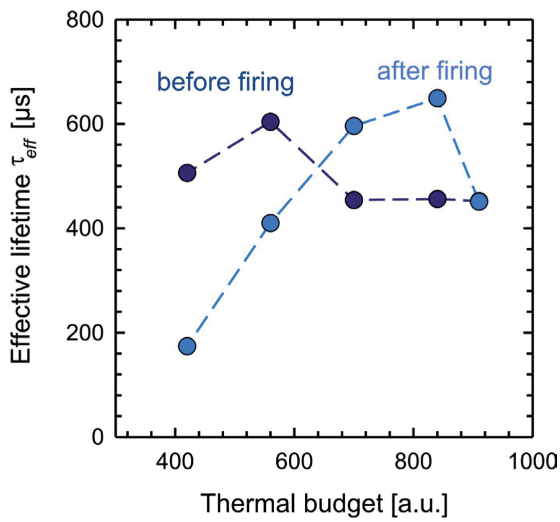

Figure 3. Effective lifetime of 20nm-thick ICP AlO_x layers capped with an ICP SiN_y layer (Singular/Singulus) on 156mm × 156mm, 2Ωcm Cz wafers. After firing, the effective lifetime strongly increases with increasing thermal budget prior to SiN_y deposition.

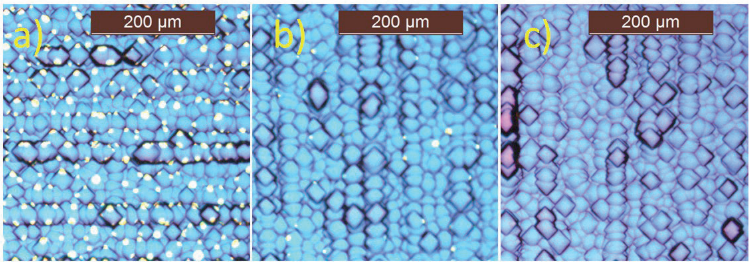

Figure 4. Light microscope images of the ICP AlO_x/ICP SiN_y-covered wafer surfaces of Fig. 3 after firing, for thermal budgets (prior to SiN_y deposition) of: (a) 420, (b) 560, and (c) 840. A greater thermal budget reduces the blistering (white dots) and hence improves the surface passivation after firing.

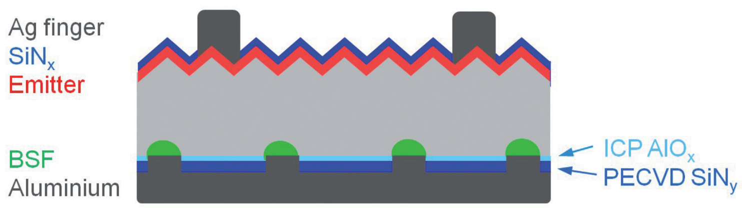

Figure 5. Schematic of the PERC solar cells with screen-printed front and rear contacts, and the application of an ICP AlO_x/SiN_y rear passivation stack.

[14] from Singulus Technologies, which uses an ICP plasma source. The ICP AlO_x layers applied in this study have a layer thickness of 20nm. It has previously been reported that an appropriate annealing of ALD Al_2O_3 layers prior to SiN_y deposition reduces blistering and hence improves the passivation quality after firing [19].

The Singular tool is designed so that a pre-heating chamber heats the silicon wafers prior to the ICP SiN_y deposition. Accordingly, the thermal budget of the pre-heating chamber prior to SiN_y deposition is varied in order to optimize the passivation quality of the ICP AlO_x/ICP SiN_y layers. The passivation layer stacks are deposited on both sides of 156mm × 156mm, 2Ωcm Czochralski (Cz) wafers. Industrial-type wafers are used in this case in order to allow a direct comparison of the resulting test wafer temperatures such as would occur in industrial cell processing.

Before firing, only a moderate dependence of the effective lifetime on the thermal budget is seen, as illustrated in Fig. 3. After firing at 900°C, however, the dependence changes: a strong increase of the effective lifetime with increasing thermal budget is found, and an optimum lifetime of around 600µs is observed. The light microscope images in Fig. 4 confirm that the increased thermal budget reduces the blistering of the ICP AlO_x/ICP SiN_y layers after firing, which explains the improvement of the effective lifetime resulting from the improved surface passivation of the ICP AlO_x/ICP SiN_y layer stack.

Application of ICP AlO_x/SiN_y layer stacks to high-efficiency screen-printed PERC cells

Rear surface passivation using ICP AlO_x/SiN_y

layer stacks was implemented for industrial-type high-efficiency PERC solar cells with screen-printed metal front and rear contacts. The process sequence of the PERC solar cells is very similar to the process sequence reported in detail in Dullweber et al. [20], so only the most important process steps will be highlighted here.

Industry-standard 156mm × 156mm, boron-doped Cz silicon wafers with resistivities of 2–3Ωcm and starting thicknesses of 200μm are used. Before texturing and phosphorus diffusion, a dielectric protection layer is deposited on the rear side of the wafer, leaving the rear side planar and non-diffused. A homogeneously doped phosphorus emitter with a sheet resistance of about 60Ω/sq. is employed. Next, an AlO_x layer is deposited on the rear side by means of the ICP deposition process as described earlier. Two different ICP AlO_x layer thicknesses of 20nm and 30nm are evaluated and compared to a 10nm-thick ALD Al_2O_3 layer as the reference.

A PECVD SiN_y (SiNA/Roth & Rau) capping layer is then deposited on top of the AlO_x passivation layer at the rear in order to improve both the optical reflectivity and the surface passivation quality. Alternatively, an ICP SiN_y (Singular/Singulus) capping layer with a thermal budget of 900 is deposited. The emitter is covered with a SiN_x anti-reflective coating. The dielectric layer stacks at the rear are locally ablated by laser contact opening (LCO) in order to form local line openings [21,22]. Line contacts are chosen instead of point contacts, since line openings facilitate the formation of a deep and uniform local Al-BSF [23]. The Ag front contacts are deposited by a print-on-print (PoP) screen-printing process, resulting in a finger width of around 70μm and a shadowing loss (including bus bars) of around 6.2% [24]. The Al rear contact is formed by full-area Al screen printing, in which a commercially available Al paste designed for local contacts is applied.

A schematic drawing of the cross section of the resulting PERC solar cell is shown in Fig. 5, and photographs of the front and rear sides are shown in Fig. 6. The contact lines are clearly visible on the cell rear side as well as on the rear passivation layer.

“The PERC solar cell with a 30nm ICP AlO_x layer achieves an independently confirmed conversion efficiency of 20.1%.”

Table 1 summarizes the *I-V* parameters of the best solar cells of each split group. The PERC solar cell with a 30nm ICP AlO_x layer achieves an independently

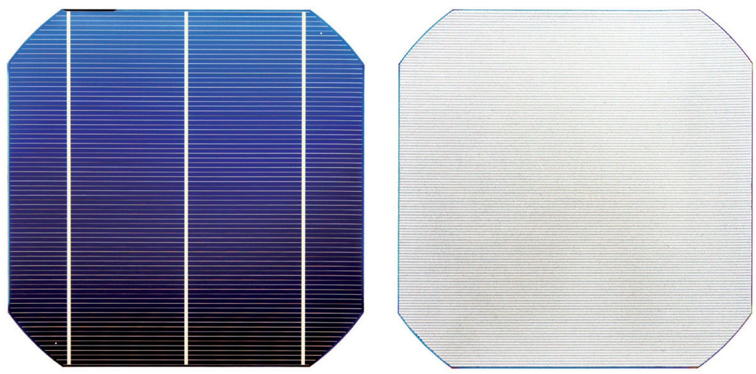

Figure 6. Photographs of the front and rear sides of a PERC solar cell with 20.1% conversion efficiency. Whereas the front side is very similar to industry-standard screen-printed solar cells, the rear side shows the ICP AlO_x/SiN_y passivation layer and the local line contacts.

Rear side passivation	AlO_x layer thickness [nm]	V_{oc} [mV]	J_{sc} [mA/cm²]	*FF* [%]	η [%]
ICP AlO_x/PECVD SiN_y	30	655	39.0	78.8	20.1*
ICP AlO_x/PECVD SiN_y	20	657	39.1	77.8	20.0*
ICP AlO_x/ICP SiN_y	20	649	39.4	77.5	19.8
ALD Al_2O_3/PECVD SiN_y	10	656	39.2	76.9	19.8*
Al-BSF	N/A	638	37.1	79.1	18.7

* Independently confirmed at Fraunhofer ISE CalLab.

Table 1. *I-V* parameters measured under standard testing conditions (STC) of 156mm × 156mm p-type Cz PERC silicon solar cells. The ICP AlO_x/SiN_y-passivated cells achieve conversion efficiencies of up to 20.1%.

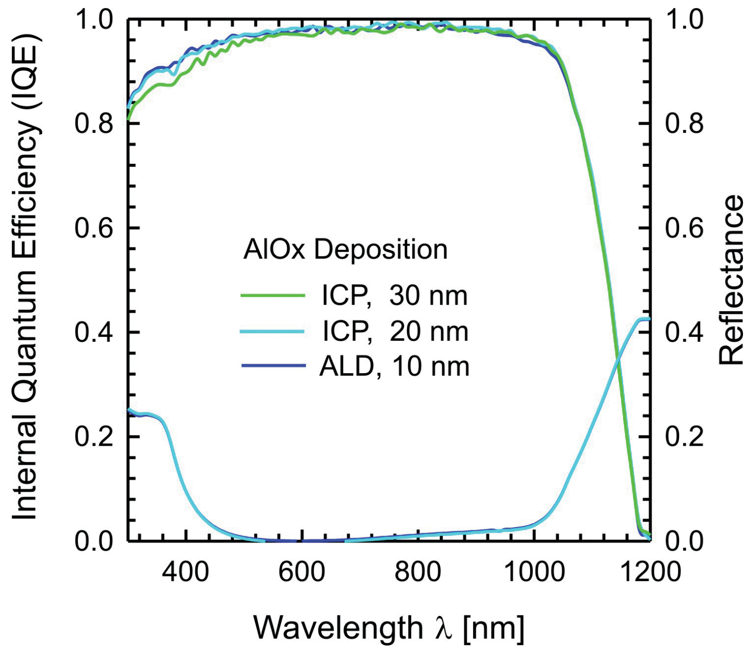

Figure 7. IQE and reflectance of the PERC solar cells of Table 1. S_{rear} values of 80–150cm/s and R_b values of 90–92% are obtained by analytical modelling, demonstrating the excellent electrical and optical parameters of the ICP AlO_x/SiN_y passivation stacks.

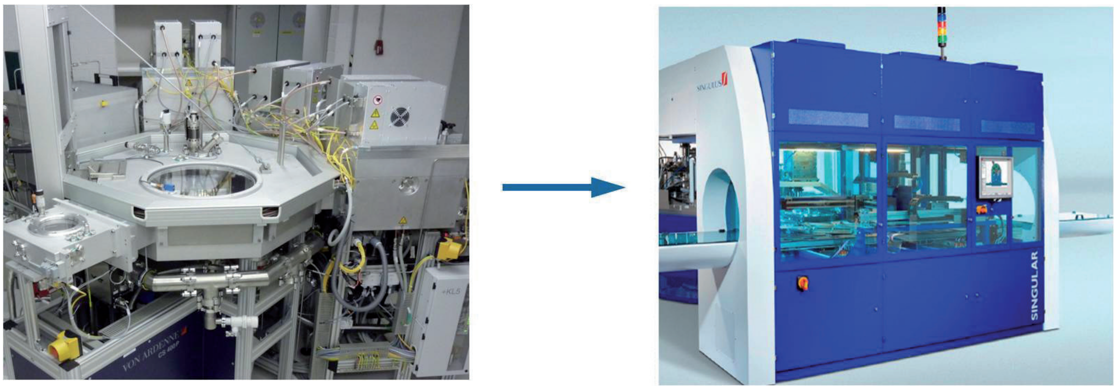

Figure 8. The ICP AlO_x process is currently being transferred from the ISFH lab tool (left) to the Singular production tool (right) for the commercialization of this novel passivation layer during 2012.

confirmed conversion efficiency of 20.1%, which is one of the highest efficiencies reported so far for industrial solar cells of this type. The high values of V_{oc} (655mV) and J_{sc} (39.0mA/cm^2) indicate the excellent rear side passivation by the ICP AlO_x/PECVD SiN_y stack. The PERC solar cells with the 20nm ICP AlO_x layer exhibit similar *I-V* parameters for both PECVD (SiNA/Roth & Rau) and ICP SiN_y (Singular/Singulus) capping layers. The reference PERC solar cell with ALD Al_2O_3/SiN_y rear passivation displays similar solar cell parameters as well.

Table 1 also includes the *I-V* parameters of an industry-standard screen-printed solar cell with full-area Al-BSF and a conversion efficiency of 18.7%. As can be seen by comparison, the significant efficiency improvement of the PERC solar cells compared to the full-area Al-BSF cell is mainly due to improved V_{oc} and J_{sc} values as a result of the improved electrical and optical properties of the rear side.

IQE analysis of screen-printed PERC cells with ICP AlO_x/SiN_y rear passivation

Fig. 7 shows the IQE and reflectance of the PERC solar cells in Table 1. The rear passivation layer mainly affects the reflectance and IQE in the wavelength range of 900nm to 1200nm. As can be seen in Fig. 6, the PERC solar cells show almost identical IQE and reflectance values in this particular range. By analytical modelling it is possible to obtain effective rear surface recombination velocities S_{rear} of 80–150cm/s and internal rear reflectances R_b of 90–92%, showing the excellent electrical and optical properties of the ICP AlO_x/SiN_y passivation stacks; these properties are almost identical to those of the ALD Al_2O_3/SiN_y stack.

"The ICP process has been demonstrated to be very well suited to the deposition of high-quality AlO_x passivation layers."

Conclusions and outlook

A novel deposition technique has been developed for AlO_x layers, in which an ICP PECVD deposition process is applied, allowing high deposition rates of up to 5nm/s. Experiments on test wafers have demonstrated an excellent surface passivation quality of the resulting ICP AlO_x layers, with surface recombination velocities after firing reduced to 7.5cm/s when applying a SiN_y capping layer. A strong increase of the passivation quality was achieved by appropriate annealing of the ICP AlO_x layer in the pre-heating chamber of the Singular tool prior to SiN_y deposition. Industrial-type PERC solar cells with an ICP AlO_x/SiN_y rear passivation stack applied have exhibited conversion efficiencies of up to 20.1%, which is one of the highest conversion efficiencies reported so far for these types of solar cell.

An IQE analysis revealed an excellent rear surface recombination velocity of 110±30cm/s and a high internal optical reflectance of 91±1%. The rear surface recombination velocity S_{rear} of 100cm/s of the PERC cells was in good accordance with the effective surface recombination velocity S_{max} of 10cm/s for test wafers, taking into account the additional contribution of the local Al contacts with surface recombination velocities S_{met} of around 400cm/s [23]. To our knowledge, this is the first time that the ICP process has been demonstrated to be very well suited to the deposition of high-quality AlO_x passivation layers. The ICP AlO_x process is currently being transferred from the ISFH lab tool to the Singular production tool of Singulus Technologies in order to commercialize this novel passivation layer during 2012.

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