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Theoretical Biosensor Design for Gold- PVA Surface Plasmon Resonance Layers

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Abstract

Surface Plasmon Resonance (SPR) technology has been employed in biosensor applications and adapted to produce a sensitive optical sensor.. Simulation analysis (using Matlab) has been done for SPR for gold (Au) layer with thickness (40 nm) and Polyvinyl Alcohol (PVA) polymer with various thickness (10, 20, 30, 40, 50, 60, 70 and 80 nm) deposited on glass prism type D-ZLAF50_Dense lanthanum flint. The sensitive layer was air (n=1). The analysis was taken for different wavelengths from ultra- violet of wavelength 100 nm to near infra- red wavelength of 1000 nm. The properties of θ_{SPR} was calculated from plots of reflectance against incident angle θincid.. The SPR sensitivity (S) was calculated. The results gave efficient detection in change of sensitive layer refractive index (0, 0.04, 0.08 and 0.12), the maximum obtained sensitivity was 207.5 for (PVA) thickness of 30 nm and 40 nm, Δn= 0.08 at wavelength 800nm and 1000nm, respectively. The best sensitivity in visible region (700 nm) was 158.33 for thickness 20nm, Δn= 0.12.

Keywords: Surface Plasmon Resonance, Gold, PVA, Theoretical model, Biosensor.

تصميم نظري لمستشعر حيوي لطبقات الرنين البلازموني السطحي بوبي فينيل الكحول– الذهب

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الخلاصة

تم تكييف تقنية الرنين البلازموني للسطح (SPR)لإنتاج مستشعر بصري حساس وتطبيقاته كمتحسس حيوي. تم إجراء تحليل المحاكاة في لغة (Matlab) للرنين البلازموني للسطح لطبقة الذهب (Au) بسمك (40 نانومتر) وبوليمر بولي فينيل الكحول (PVA) باسماك مختلفة (10 ، 20 ، 30 ، 40 ، 50 ، 60 ، 70 و 80 نانومتر) المترسبة على الموشور الزجاجي من النوع _D-ZLAF50 اللانثانوم الكثيف الصوان. كانت الطبقة الحساسة عبارة عن هواء (n=1). تم أخذ التحليل لأطوال موجية مختلفة من الطول الموجي فوق البنفسجي 100 نانومتر إلى الطول الموجي القريب من الأشعة تحت الحمراء 1000 نانومتر. تم حساب خصائص θ_{SPR} من مخطط الانعكاس مقابل زاوية السقوط (θ_{incid}) .تم حساب الحساسية (S) SPR بينت

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النتائج كشفًا فعالًا في تغير معامل الانكسار للطبقة الحساسة (0 ، 0.04 ، 0.08 ، 0.12) ، وتم الحصول على أقصى حساسية 207.5 لسمك (PVA) 30 و 50 نانومتر ، Δn = 0.08 عند الطول الموجي 800 نانومتر و 1000 نانومتر ، على التوالي. أفضل حساسية في المنطقة المرئية (700 نانومتر) هي 158.33 للسمك 20 نانومتر، Δn = 0.12 .

1. Introduction

Surface plasmon is characterized as oscillations of free electrons in metal that, when excited by optical radiation, cause electromagnetic waves at the metal-dielectric interface, known as surface plasmon waves [1]. SPR sensors have become a principal technology due to its distinctive and varied properties, such as: fast response (Responsiveness), small volume, and large sensitivity to medium of different refractive index [2]. SPR is a sensitive technique for observing changes in optical properties in the speedy vicinity of a sensor surface.It is very suitable in bio sensing and surface science research [3], because of its great sensitive behavior, and capability for label-free sensing. This phenomenon has been emphasized as a controlling optical detection technique [4-6].

The sensing operation of a Surface Plasmon Resonance (SPR) detector depends on the plasmonic material working in this design. Modern plasmonic detectors mostly use gold because of several advantageous characteristic: it is chemically inert, long-term steady, and easy to structure [7]. So that, it has greater optical damping and broader resonance wavelength peak leading to false positive analytic detections [8].

SPR has been an extensively used as an optical technique for the actual time and label free sensing applications in biomedicine. Surface Plasmon resonance is being widely sensitive to the surrounding media; their feature can be modulated by setting their dielectric environment [9].

The excitation of Plasmon's surface polarizations (SPPS) through a prism is highly dependent on the incident light polarization, the complex refractive index of metal, the metal layer thickness, the optical properties of the dielectric material, and the light beam incident angle. In this research, a variation of boundaries has been demonstrated. First, the plasmonic activity of the change of gold thickness (Au) and polyvinyl alcohol (PVA) is evaluated under different wavelengths from UV to near infrared.

2. Methodology

In spite of the new understanding of light − matter interfaces, there still persist many obscures, specifically, if the matter is in shape of particles or structures whose linear dimensions are equivalent to or smaller than the wavelength of light. In this situation, the optical properties are very different from those of the identical bulk material. The electromagnetic field will possibly be at resonance with oscillations corresponding to the layers' conduction electrons. This will lead to a great increase of the absorption of the incoming light . This phenomenon is termed localized surface plasmon resonances (LSPRs).

As soon as the photons beam hits the material, the electromagnetic wave is spread at the interface between the two media even if both are transparent. Reflectivity (R) is the portion of the incident electromagnetic wave that is reflected at the interface, and is known by [10]:

$$R = \frac{I_r}{I_o} \tag{1}$$

Where I_o is the incident beam intensity and I_r is the reflected beam intensity.
The reflectivity (R) for normal incidence between any two media is given by [10]:

$$R = ((n - n\_i)/(n + n\_i\ ))^2 \tag{2}$$

Where n& n_i are the reflective index for first and second medium, respectively.

Adapt the light reflection from a specific surface to equations (1&2) and use normal incidence. The reflectivity value can be influenced by the incidence angle. Some materials with high refractive index have a high reflectivity in comparison to materials with low refractive index. Due to the fact that refractive index differs with photon wavelength, high

reflectivity of metals is the first reason that they are an opaque. High reflectivity is required in many applications excluding mirrors, coatings on glasses, etc.[10]
The surface plasmon resonance condition is given as [12]:

$$K_{SPR} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_r \varepsilon_i}{\varepsilon_r - \varepsilon_i}} \quad (3)$$

Where light speed in free space is c, frequency of light is ω, and the dielectric constants of metal and medium in contact with the metal are ε_1, ε_2, respectively.
The metal dielectric constant is given by [12]:

$$\varepsilon = \varepsilon_r - i\varepsilon_i \quad (4)$$

which is associated with optical constants by the relation:

$$\varepsilon_r = n^2 - K^2 \quad \text{and} \quad \varepsilon_i = 2nK \quad (5)$$

n and k are the refractive index and the extinction coefficient of the medium, respectively. Many light reflections and transmissions happens when monochromatic incident light falls with an angle θ on a thin metal film over a prism. . Changing the angle of incidence, minimum reflectance can occur. At certain incident angles, surface plasmon is excited and resonated beside the interface between the metal and dielectric. Phase matching gain takes place when the angle of incidence on the prism is larger than the critical angle [13]. In highest surface plasmon resonance (SPR) tests, silver or gold are extensively used as a thin layer (film) on the prism surface. The shape of the full resonance curve is determined mainly by the thickness and optical assets of the metal layer [14, 15].

The reflected light measured against the change of the resonance peak incident angle defines the sensitivity of a sensor (S_n) . A large change in the resonance angle for a small change in refractive index is required for high sensitivity of a sensor , as defined by the equation [16]:

$$S_n = \frac{\partial \theta_{SPR}}{\partial n} \quad (6)$$

Based on phase interrogation, $\partial\theta_{SPR}$ is the difference in the dip location of the reflected light at the resonance angle, and ∂n is the variation in refractive index.

There are several studies about SPR sensors, such as SPR effect modeling executed in MATLAB and Mathcad was offered in the literature as beneficial to control the designing optical sensors parameters. Fontana in (2006) [14] used Mathcad to determine the wavelength dependency of the optimal thickness for the maximum sensitivity of the SPR effect. In addition, Yang H. et al. (2011) [3] used MATLAB program to proposal a prism-based SPR sensor based on Kretschmann's arrangement, considering angular interrogation (AIM) and wavelength interrogation (WIM) modes. Kaneoka Y. et al. (2016) [16] proposed a method to measure the thickness of a dielectric layer coating a metal surface. A five-layer structure composed of :glass prism type BK7, air gap, polyvinyl alcohol (PVA) which was used as the dielectric core layer material, gold film and BK7 substrate, was used as an optical model for the measurements. The method proved to be useful for measuring dielectric thickness with a range from a few nanometers to one micrometer. The excitation light beam wavelength is regular to be 632.8 nm and it was assumed that the PVA film had no light absorption in this region.
In this work, the simulation analysis (in Matlab) consists of two layers (N = 2) (as shown in Figure 1): a half-cylinder glass prism type D-ZLAF50_ dense lanthanum flint, over which a gold layer of thickness (40) nm, is deposited, and Polyvinyl Alcohol (PVA) polymer with various thickness (10, 20, 30, 40, 50, 60, 70 and 80)nm, with air (n_{air} = 1) as the sensitive medium . The excitation light beam was of different wavelengths from ultra- violet of wavelength= 100 nm to near infra- red wavelength 1000 nm.

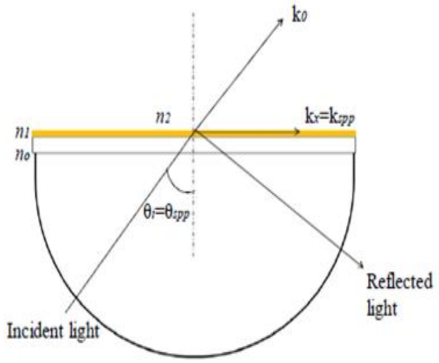


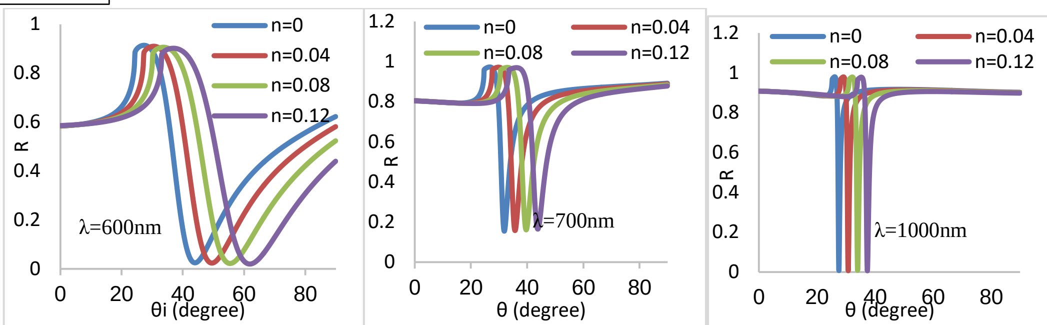
Figure 1-half-cylinder glass prism [17]

3. Results and Discussions

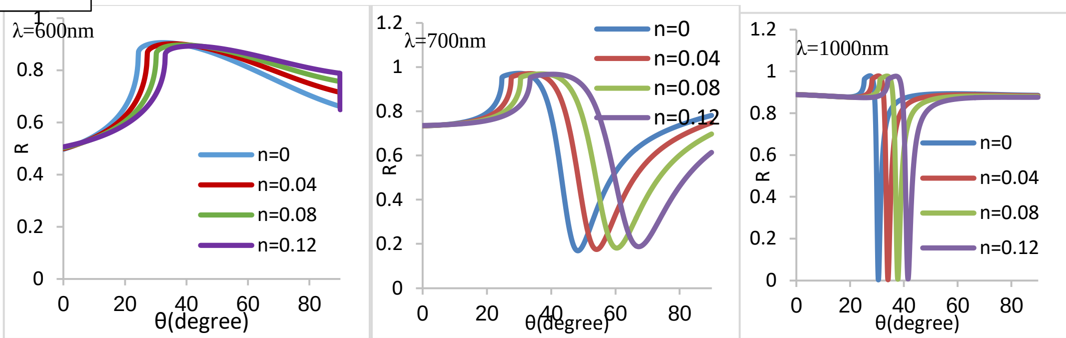
The influence of different layer thicknesses was studied . Reflectivity (R) was plotted against the angle of incidence(θ) for different refractive indices at different PVA thicknesses (t_{PVA}= 10-80)nm and at different wavelengths and from ultraviolet (100nm) to near IR (1000nm) (as illustrated in Figure 2). The thickness of gold thin film was (40) nm. SPR peak does not appear at wavelengths below 600nm for all thickness of PVA layer. From Figure 2, it is noticed that, at t_{PVA} =10 nm, the best SPR was at 700nm wavelength. At 20nm, SPR peak shifted towards the IR region. While , it was noticed that when the thickness layer increased from 30 nm and 40 nm, SPR peak vanished at all wavelengths except at the IR region. At t=50 nm to 80 nm, it appeared at the visible region, as shown in Table 1.

The effect changing the refractive index of the sensitive outer media from n =0 to 0.12, in steps of 0.04, was clear in that the SPR peak appeared at bigger incidence angles as the refractive index was increased. This was true for all PVA thickness and at all wavelengths. reflectivity was constant at the same value. When the thickness enlarged from 10 nm to 80 nm, the reflectivity of SPR peak decreased but the resonance angle varied.

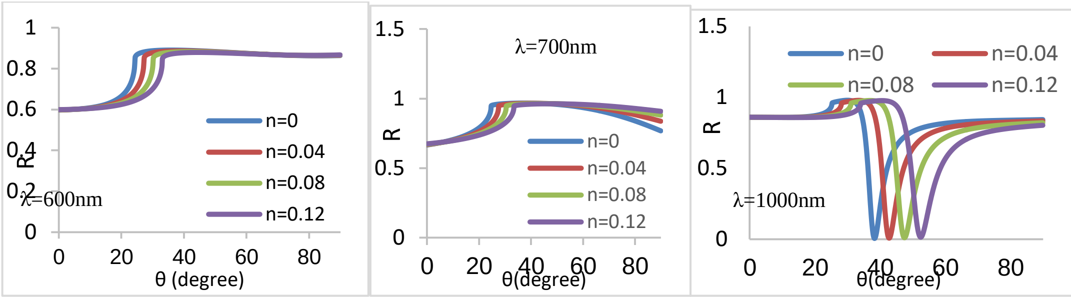
t_{pva} =10 nm



t_{PVA}=20nm



t_{PVA}=30nm



t_{PVA}=40nm

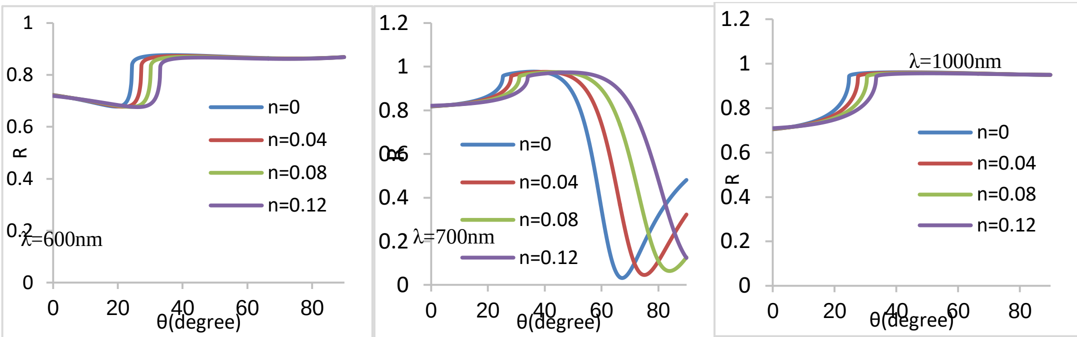
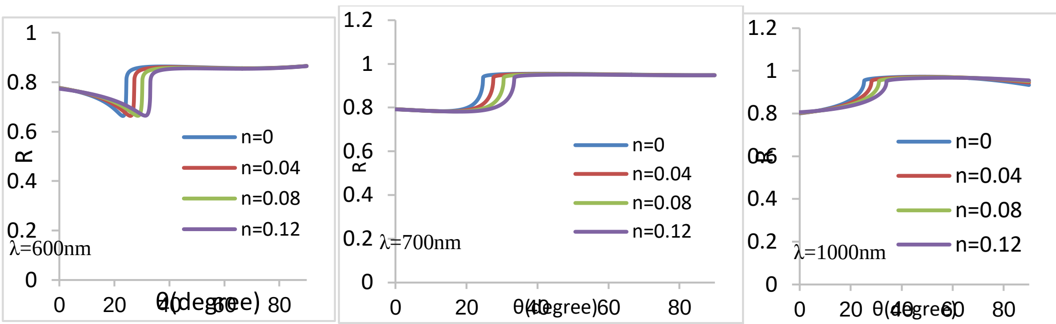
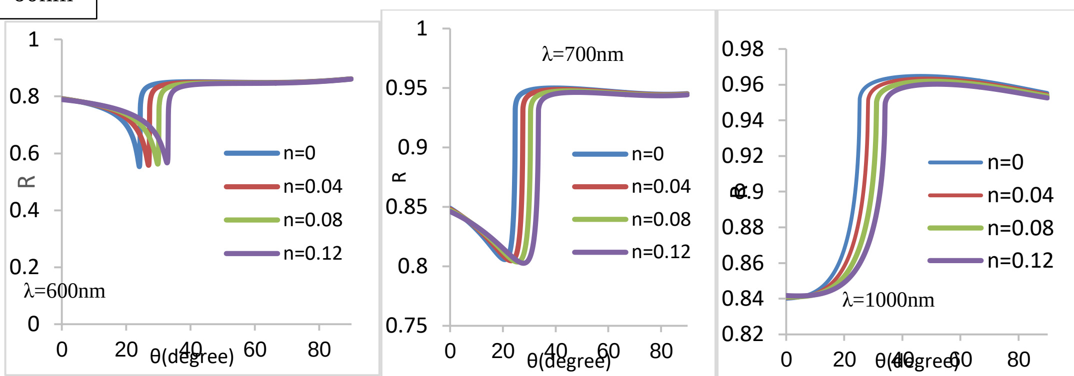


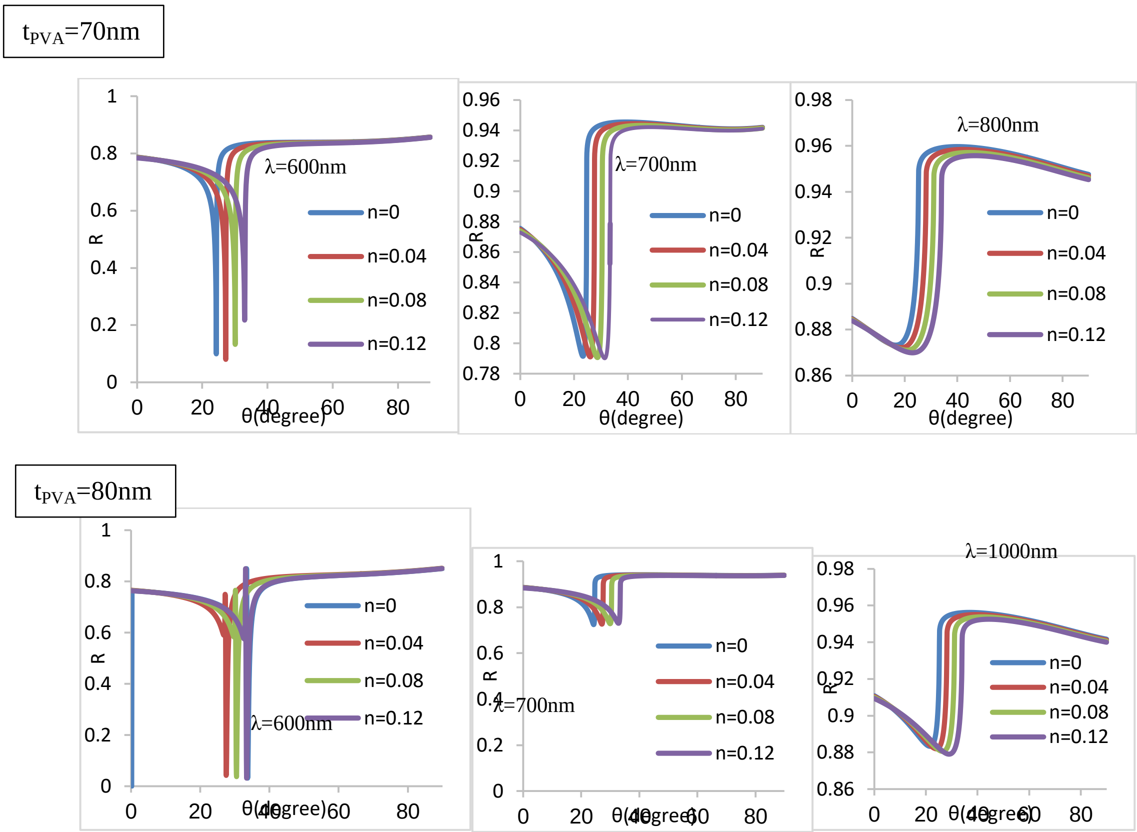
Figure (2): Variation of reflectivity with respect to the incident angle for different thickness of PVA (10, 20, 30, 40, 50, 60, 70 and 80)nm, and various sensitive refractive indices.

t_{PVA}=50nm



t_{PVA}=60nm





Continue Figure (2)

The relationship between sensitivity, calculated from Eq. (6), with respect to change of thickness of the sensitive PVA layer and change of the refractive index is illustrated in Table 1. It is clear that maximum sensitivity of 207.5 is obtained in two cases at t_{PVA}= 30nm, Δn= 0.08 and at a wavelength of 800 nm , also, at t_{PVA}=40 nm, Δn= 0.08 in the IR region (1000nm). For small thickness of PVA layer , the sensitivity may be best. As the thickness increases , the sensitivity becomes less . The best sensitivity in visible region (700 nm) was equal to 158.33 for PVA thickness 20nm, and for Δn= 0.12.

The results gave efficient detection in change of sensitive layer refractive index (0, 0.04, 0.08 and 0.12), and the best sensitivity of 207.5 was for PVA thickness of 30nm and 40nm at wavelength 800nm and 1000nm, respectively.

Table 1-Sensitivity with respect to thickness of PVA layer at different wavelength and change refractive index.

t_{PVA}(nm)	**λ(nm)**	**Sensitivity (S)=ΔΘ/Δn**		
		Δn= 0.04	**Δn= 0.08**	**Δn= 0.12**
10	100-500	------------	---------	----------
	600	137.5	142.5	149.16
	700	95	97.5	99.16
	800	87.5	87.5	89.16
	900	82.5	83.57	84.16
	1000	80	80	81.16
20	100-600	---------------	----------------	------------
	700	145	151.25	158.33

	800	110	112.5	115
	900	97.5	97.5	100
	1000	90	91.25	91.66
30	100-700	---------------	----------------	-----------
	800	195	207.5	186.6
	900	137.5	141.25	146.66
	1000	112.5	115	118.3
40	100-900	---------------	--------------	-----------
	1000	195	207.5	--------
50	100-400	-------------	-----------	-------------
	500	72.5	72.5	72.5
	600	67.5	67.5	67.5
	700-1000	-------------	------------	------------
60	100-400	------------	----------	-----------
	500	72.5	72.5	73.3
	600	72.5	71.25	71.66
	700-1000	------------	----------	---------
70	100-400	---------	--------	-------
	500	72.5	72.5	73.3
	600	72.5	72.5	72.5
	700-1000	---------	-----------	-------
80	100-400	----------	-----------	----------
	500	72.5	73.75	74.16
	600	72.5	73.75	73.33
	700-1000	-------------	------------	--------

4. Conclusions

In this paper, the simulation analysis was suggested to calculate the SPR effect as a multilayer structure. Simulation-SPR is devoted to evaluate reflectance of half-cylinder glass prism type D-ZLAF50_Dense lanthanum flint. The SPR sensitivity (S) and the properties of θ_{SPR} were calculated from reflectivity against incident angle (θ)curves at various wavelengths from ultraviolet to near infrared regions. It was shown that the changes in the SPR depend on the thickness of the PVA sensitive layer and on the incident wavelength. The surface plasmon resonance angle (θ_{SPR}) shifted to higher values with the increase of thickness . Maximum sensitivity of 207.5 for PVA thickness of 30 nm and 40 nm at wavelengths of 800nm and 1000nm, respectively was obtained.

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