Microelectromechanical spatial light modulators with integrated electronics

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1. ABSTRACT

This paper describes design and development of a microelectromechanical, micromachined spatial light modulator (μSLM) integrated with complementary metal-oxide semiconductor (CMOS) electronics, for control of optical phase in phase-only optical correlators. The μSLM will consist of a large array of piston-motion MEMS mirror segments (pixels) each of which capable of altering the phase of reflected light by up to one wavelength for infrared (1.5 μm) illumination. Results of a proof-of-concept study are presented along with an electromechanical model and details of the fabrication process for the μSLM

KEYWORDS: spatial light modulator, MEMS, micromirror

2. INTRODUCTION

A new class of spatial light modulator based on full vertical integration of CMOS electronics and surface micromachined piston mirrors is under development at Boston University's Precision Engineering Research Laboratory. The micromachined spatial light modulator (μSLM) will consist of an array of 1024 piston motion MEMS mirror segments fabricated in aluminum over a 10 mm square aperture. Each pixel will be capable of altering the phase of reflected light by up to one wavelength for visible light, controlled by an underlying multi-bit digital CMOS driver that will provide a high degree of resolution. Mirror elements will be more than 90% reflective and will be optically flat and smooth. The array will be digitally updated at a rate of 10kHz. Light modulation will be phase-only, with uniform reflected intensity. Mirror fill factor of 98% will be achievable for square pixel sizes 100 micrometers on a side. Fabrication will make use of a novel low-temperature batch surface-micromachining process integrated with commercially available low-cost foundry electronics fabrication, the device will be economical, reliable, and scalable. Figure 1 shows a schematic of nine mirror pixels in the proposed μSLM.

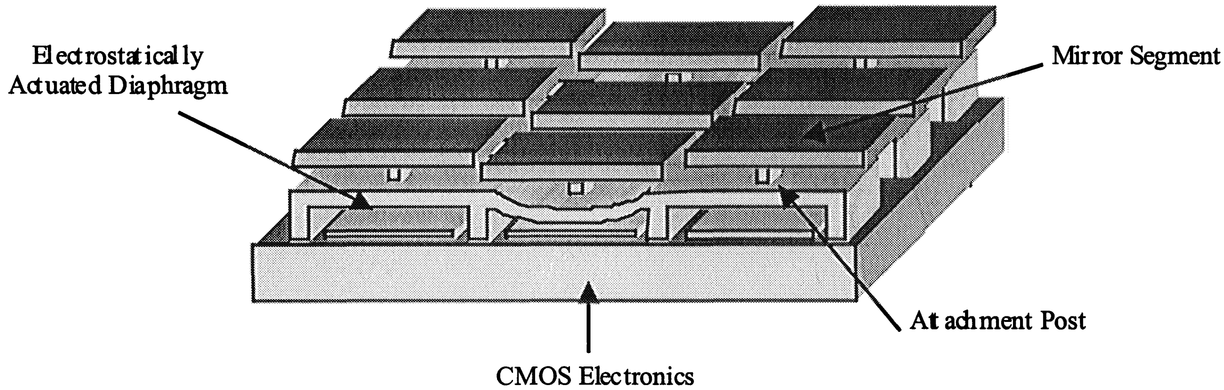

Figure 1. Cross-sectional schematic of three elements in a micro-machined spatial light modulator (μSLM).

In this low temperature MEMS fabrication process, patterned thin layers of structural and sacrificial materials will be built up on a substrate through sequential deposition and lithography. Ultimately, the sacrificial layers will be etched away, leaving a self-assembled, integrated opto-electromechanical device. The phase of each individual

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mirror segment will be controlled by a CMOS data register integrated beneath a parallel-plate electrostatic actuator. The actuation electrode will be divided into concentric rings connected electrically to the underlying CMOS driver. Each ring will have successively larger area, in a geometric sequence, and each will be driven by a binary signal of 0 or 17V. Electrostatic actuation holds considerable promise for SLM shape control because it offers nearly reversible (i.e. low power) actuation, no hysteresis, several micrometers of stroke, and nanometer-scale precision and repeatability.

3. BACKGROUND

Actuator fabrication has been studied, with an emphasis on defining suitable metal deposition processes and reducing residual strain gradients (and resulting curvature) in thin-film metal structures. Both DC magnetron sputtering and e-beam evaporation were evaluated as metal deposition techniques. Titanium and aluminum structural materials were tested. The results, summarized in the table below, indicate that DC sputtering of aluminum offers the most promising approach for development of actuators, primarily because of the wide range of processing conditions available with sputtering and the low annealing temperature of aluminum.

Parameter	***Titanium***	***Aluminum***
Residual Stress	*Highly tensile*	*Variable*
Required Anneal Temperature	*600°C (too high for CMOS)*	*200°C (Acceptable for CMOS)*

Table 2. Evaluation of μSLM material parameters

Parameter	***Evaporation***	***Sputtering***
Deposition Rates	*162Å/min*	*20 - 300Å/min*
Residual Stress	*Highly tensile*	*Tensile to compressive, depending on pressure and sputtering power*

Table 1. Evaluation of aluminum deposition parameters

Metal was deposited on a patterned photoresist film atop a glass substrate. Lithographic patterning of the deposited metal film was achieved by wet-etching of the metal through a second photoresist mask (Shipley® 1813). After metal patterning, the devices were released by dissolving all photoresist in an acetone bath. Critical point drying was used to prevent stiction. Using this process, a series of aluminum actuators (see Figure 2) and mirrors were fabricated individually and in small arrays.

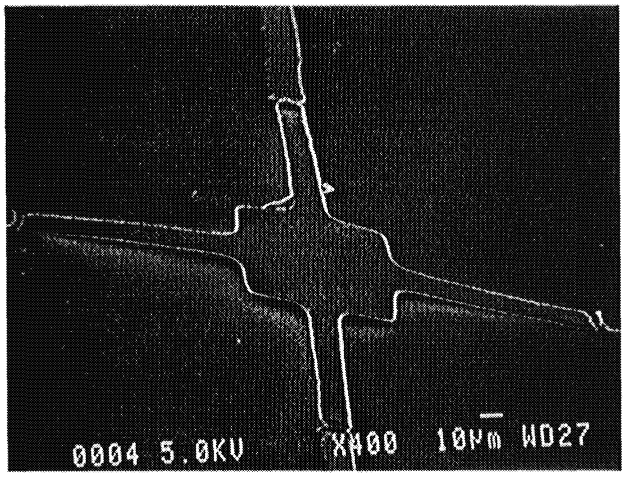

Figure 2. Proof-of-concept metal actuator

The electromechanical performance of a typical microactuator fabricated through the proposed process was characterized. Stroke and resolution were measured using an interferometric contouring microscope and an applied electrostatic actuation. Figure 3 below shows that an actuation of 1.2μm was achieved with an applied 23 volts. A greater voltage resulted in actuator "snap-through", where the electrostatic force was greater than the mechanical restoring forces of the actuator and the actuator membrane collapsed unstably toward the substrate.

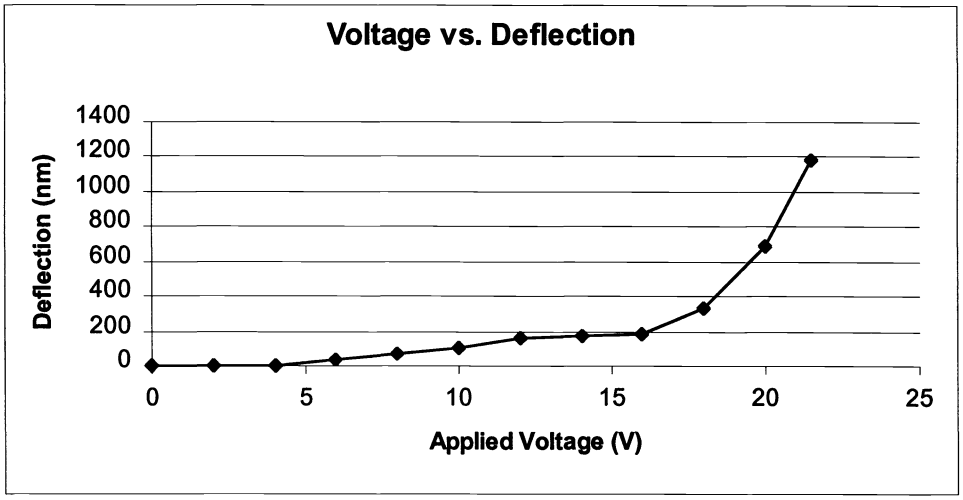

Figure 3. Applied voltage vs. deflection of a 100μm actuator

Also investigated in this study was the reduction of stress-induced curvature of thin metal micromirrors by varying sputter process conditions. Changing the partial pressure of the working gas (Argon) was shown to have an effect on the out-of-plane deformation of the released metal structure, which was measured as the average radius of curvature actuator membrane. As shown in figure 4, the radius of curvature was reduced by increasing the flow of Argon gas, thereby increasing its partial pressure.

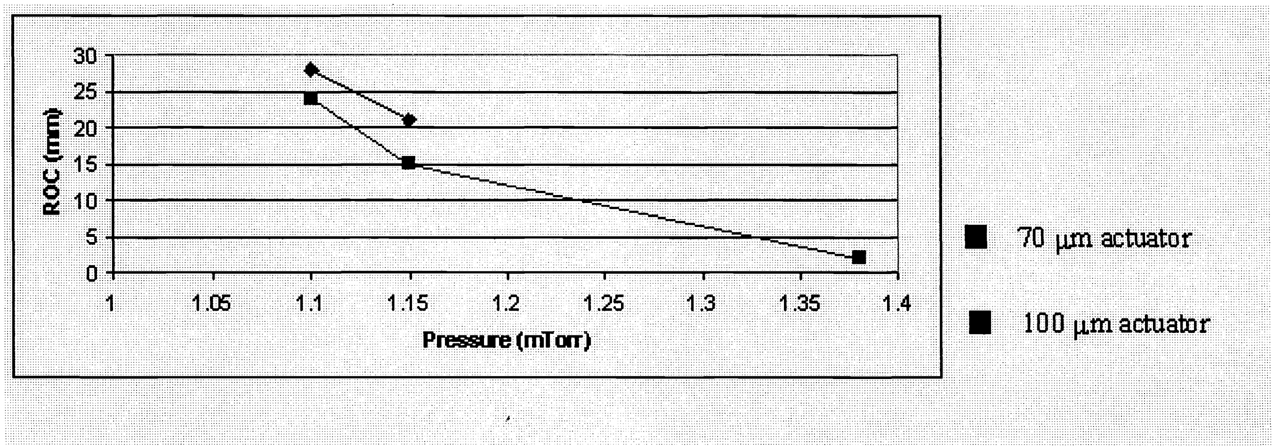

Figure 4. Partial Pressure of Working Gas versus Radius of Curvature for 2 different sizes of actuators.

4. ACTUATOR DESIGN AND ELECTROMECHANICAL MODEL

A mathematical model of the proposed actuator was developed to assist in design studies and to predict electromechanical behavior. Figure 5 shows the configuration of the actuator design in which a square membrane is supported by four flexures running parallel to the electrostatic diaphragm of the actuator. In the proposed design, each individual mirror pixel is actuated electrostatically using electrodes located beneath the square membrane. The mirrors are attached to the actuator by a post attached to the center of the membrane (not shown in figure). The actuator deflection can be determined through a force balance equation between the mechanical restoring force, F_m, and the electrostatic force, F_e establishing an electromechanical equilibrium for the actuator. The mechanical restoring force is applied to the movable actuator plate through four anchored flexure arms, modeled as fixed-guided cantilever beams; the actuator plate is assumed to be rigid.

$$F_e = F_m \qquad F_e = \frac{\varepsilon A V^2}{2(g-y)^2} \qquad F_m = \frac{4Ewt^3}{L^3} y$$

Where ε is the dielectric constant of the actuator gap, V is the voltage applied to the actuator, L is the length of the flexure arm, g is the gap between the actuator diaphragm and the substrate, y is the surface-normal deflection of the actuator plate, E is the modulus of elasticity of the actuator material, w is the width of the flexure arm, and t is the thickness of the flexure arm.

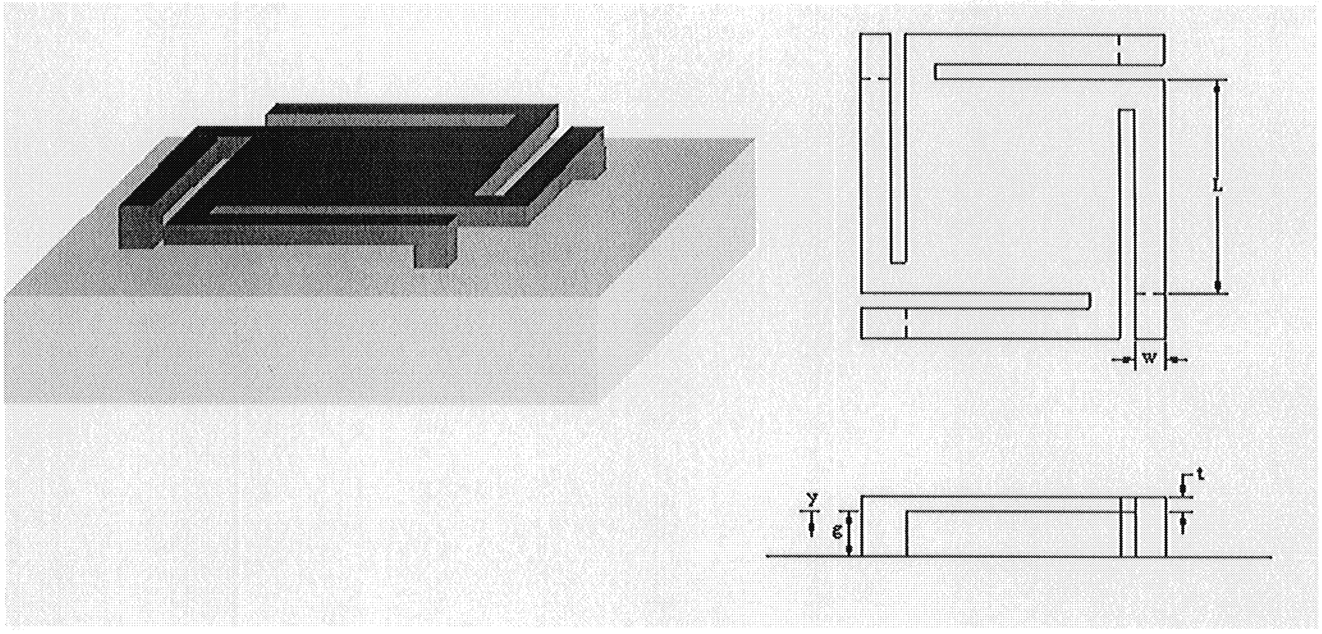

Figure 5. Actuator configuration

The µSLM design targets are listed in the table 3 below:

Parameter	Value
Driving voltage, V	17 V
Stroke	0.78µm
Minimum gap, g	2.33µm
Max membrane actuation area, A	80µm x 80µm
Natural frequency	100 kHz

Table 3. µSLM Design constraints

The minimum gap size is determined from the required stroke of 0.78 μm requiring a minimum gap size of 2.33μm to prevent snap-through from occurring prior to reaching the full actuator stroke [1]. The maximum membrane actuation area is based on a mirror size of 100 μm x 100μm and a flexure width of 5 μm. Given these size constraints and the geometry shown in Figure 5, the actuator thickness will be 1.36 μm allowing the required stroke with the maximum available voltage. Modeling the actuator/mirror as a simple mass-spring system, the proposed geometry yields a natural frequency of 44KHz. The natural frequency can be increased to the required 100 kHz by reducing actuator arm length and the actuator thickness by a factor of ~2.2.

5. FABRICATION PROCESS

A new microfabrication process is being developed for the integration of a metal μSLM with the pre-fabricated CMOS electronics. The proposed process is made up of photolithograhy, metal deposition, etching and releasing steps. All of the process steps are performed at low temperature to maintain the integrity of the CMOS device. The process is outlined in Figure 6. Vias are created first by patterning and etching through the planarization layer to an underlying electrode (step 1). Metal is deposited to make an electrical connection to the CMOS electronics (step 2). A layer of resist is than spun on and patterned, followed by a second metal deposition to form the electrodes through lift off (step 3, 4, and 5). A sacrificial layer of photoresist is spun on, the thickness of which determines the actuator gap. The actuator anchors are patterned and a third metal layer, 1.09 μm thick, is deposited (step 6 & 7). The metal 2 layer is than patterned and etched to form the actuator (step 8). Another sacrificial layer of resist is spun on and patterned to from the mirror posts after a second metal etching process. Finally, sacrificial resist layers are removed leaving an assembled MEMS device. As part of the fabrication process the metal deposition parameters, and the necessity for adding annealing steps, will be determined to minimize the residual stresses in the actuator and mirror films such that curvature will be minimized. This process can be extended from a single actuator/mirror to a large array.

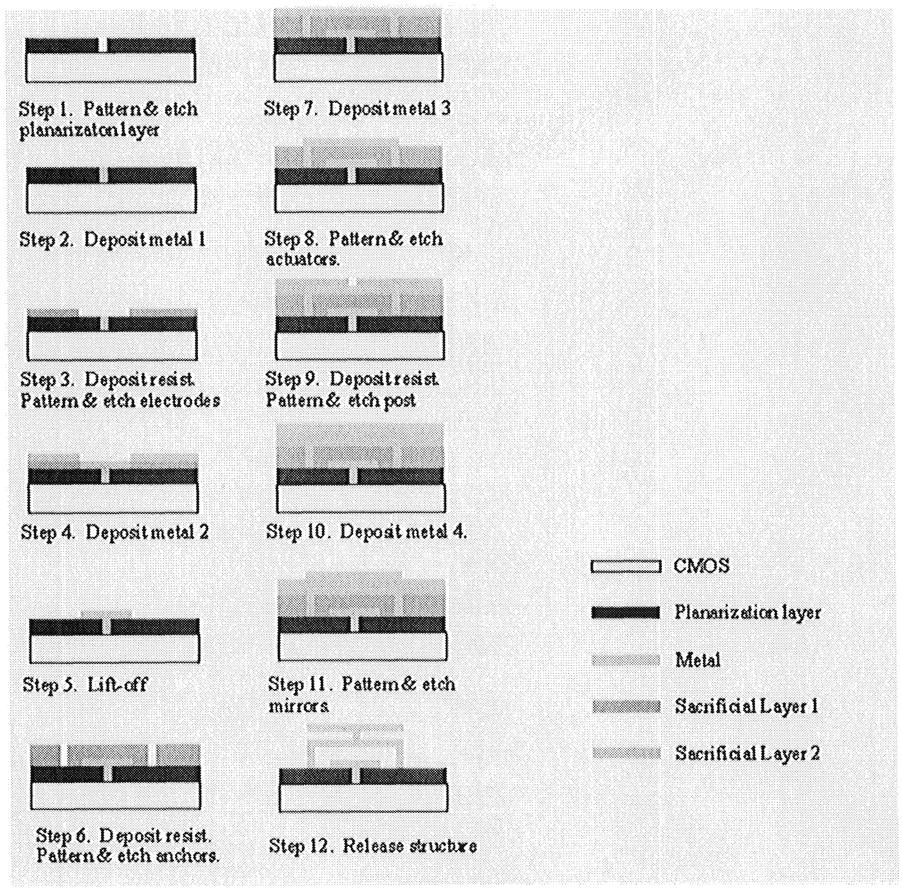

Figure 6. μSLM fabrication process

Prior to fabricating the MEMS device, the surface of the CMOS electronics requires planarization. This surface has topography resulting from its multi-layer fabrication process. A planar surface is required for the μSLM, as any topography will print through the consequent layers and reduce the performance of the actuator and the optical quality of the mirror. Planarization is approached in two ways: using 1) spin on polymers, and 2) mechanical polishing. Initial experiments performed using spin-on polymer (Futurrex PC-3-1500 planarization coating) on representative CMOS chips (3mm x 3mm) show that high frequency surface topography can be made smoother, however, the resulting film was not flat, as can be seen in Figure 7.

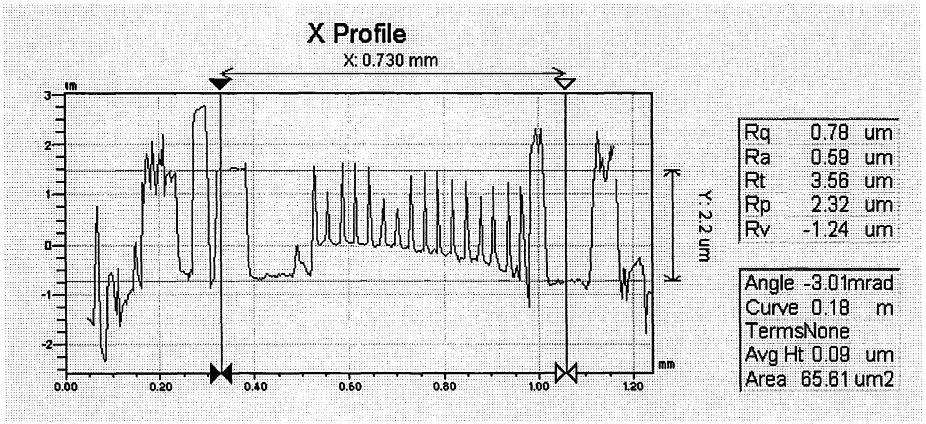

Figure 7a. CMOS topography prior to planarization coating application

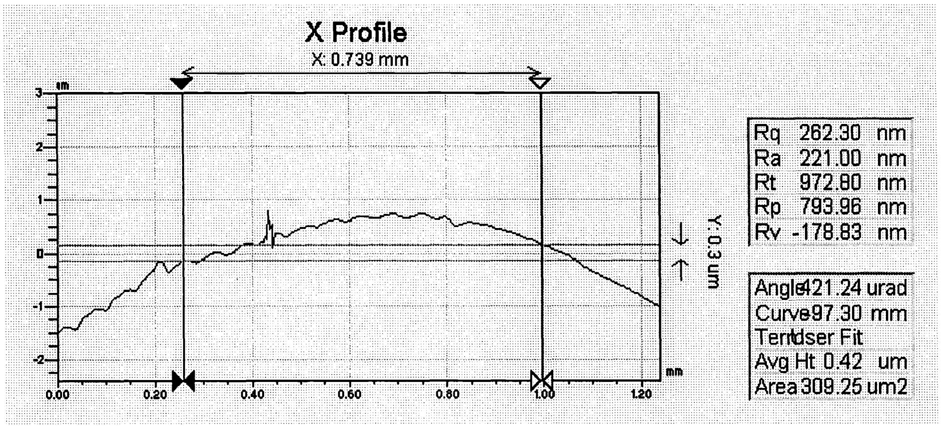

Figure 7b. CMOS topography after planarization coating application

The planarization process using the Futurrex polymer is currently being developed further to determine if improvements can be made. In addition, other polymers employed in planarization [2], are being investigated to generate a smooth, flat surface on the CMOS for the integration of the MEMS devices.

The second planarization method will be investigated in parallel and will generate a flat surface by depositing a layer of SiO2 on the CMOS circuitry and polishing this layer to a smooth, flat finish.

Up to date, experiments have been conducted to define sputtering parameters to obtain a smooth low-stress film. Thin aluminum films, approximately 200 nm thick, with high optical quality (Rq = 28nm) have been deposited on glass with good adherence. Thicker films have been deposited but have had a white, milky appearance, and high surface roughness. The whitish film seems to be indicative of the presence of oxygen during the sputtering process and is currently under investigation.

In addition, resist processing techniques are being addressed to ensure that the sacrificial layers will be stable during the processing of subsequent steps.

6. FUTURE WORK

The proposed spatial light modulator is in its early stages of development and so there is considerable work remaining. The proposed fabrication process will be developed in five phases: 1) planarization and via etching, 2) actuator fabrication, 3) mirror fabrication, 4) the integration of the actuator and the mirror, and 5) integration of the mirror array with the CMOS. The thin film characteristics for both the actuator and mirror require precise control of the sputtering process to yield films with good optical quality and controlled biaxial stress and stress gradients across the film. The actuators will be tested to verify electromechanical performance.

The resist processing and stabilization is being investigated to develop the process such that feature size and sidewall angles will be produced as desired and to ensure that features are not distorted due to subsequent processing such as resist baking, metal deposition, and/or annealing. The final challenge will be to integrate a large array of actuator/mirror pixels with the CMOS chip.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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