3D PRINTED MEMS

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ABSTRACT

3D printing at the macroscale has evolved from making plastic prototypes to the production of high-performance functional metal parts for industries such as medical and aerospace. By contrast, MEMS devices today are produced in large quantities using semiconductor manufacturing processes. However, the semiconductor manufacturing paradigm is not cost-effective for producing customized MEMS devices in small to medium volumes (tens to thousands of units per year), and related applications are difficult to address efficiently. 3D printing of functional MEMS devices could play an important role in filling this gap. Here, we discuss recent advances in 3D-printed functional MEMS, addressing the challenges of economical customization at smaller production volumes.

KEYWORDS

Additive Manufacturing, Multiphoton Lithography, 3D MEMS, Optical MEMS, Silica Glass

INTRODUCTION

Microelectromechanical systems (MEMS) are micro- and nano-scale sensor and actuator components that provide wide-ranging capabilities through delicate structural design and material selection. Over the past few decades, MEMS components, such as accelerometers, gyroscopes, pressure sensors, and microphones, have achieved significant success [1], [2]. They have become indispensable for the consumer electronics we use daily – from mobile phones to cars. Moreover, optical MEMS enable precise control of light for modulating and coupling optical signals in emerging components, such as photonic integrated circuits (PICs) and fiber optics, essential for sensing, high-speed communication, and computing[3], [4].

To date, the production of MEMS components has heavily relied on semiconductor manufacturing technologies. These technologies are optimized for manufacturing planar patterns for electronics in large volumes and, therefore, offer little freedom for creating 3D structures, restricting the performance of MEMS devices since they need to interact with mechanical forces, acoustic waves, and light that inherently feature 3D characteristics. Moreover, the high startup cost and long time required to set up a manufacturing process and validate a design idea for a MEMS component make it challenging to develop MEMS components in small and medium-sized batches.

Emerging micro 3D printing (additive manufacturing) technologies could provide a revolutionary complement to the existing MEMS manufacturing paradigm. 3D printing of micro-scale objects has attracted enormous interest in the scientific community in recent decades due to the capabilities of rapid prototyping without the need to access expensive semiconductor or nanofabrication cleanrooms. Micro 3D printing allows for the fabrication of structures with complex 3D designs and the integration of 3D printed structures onto arbitrary pre-existing objects. One of the most promising micro 3D printing technologies is multiphoton lithography (MPL) based on femtosecond laser 3D direct writing, enabling the realization of 3D microstructures with nanoscale resolution at comparably high printing speed [5]. At the same time, commercial multiphoton lithography 3D printers have become increasingly mature and available. The femtosecond lasers used in multiphoton lithography are pulsed lasers with a pulse duration shorter than a picosecond, which enables minimizing thermal effects during the transfer of the laser energy to the exposed material volume. Thus, achieving efficient multiphoton absorption in the material volume exposed to the laser to initiate chemical reactions is possible by applying an ultrahigh photon density at the focal point of the laser. For example, multiphoton absorption can cause local crosslinking of a photoresist while leaving the materials outside the focal point of the laser (voxel) unaffected. Consequently, 3D printing with nanoscale resolution can be done by direct femtosecond laser writing inside a photoresist. Here, we present an overview of recent advancements in micro 3D printing by multiphoton lithography that have enabled the realization of MEMS devices with electrical functionality. We also include investigations into expanding material options for multiphoton lithography beyond organic polymers, enabling the realization of MEMS devices with improved thermal stability, mechanical and optical properties and reliability.

3D-PRINTED MEMS DEVICES

The emergence of 3D printing by multiphoton lithography, with its nanoscale resolution and rapid prototyping without the need for access to a nanofabrication cleanroom, has enabled a new paradigm for realizing 3D structures not imaginable by using conventional semiconductor manufacturing technologies. These capabilities are directly applicable to MEMS sensors and actuators. MEMS sensors typically consist of mechanical structures that transduce environmental parameters such as acceleration, force, or pressure into measurable electrical signals.

To demonstrate the applicability of 3D printing by multiphoton lithography for realizing functional MEMS sensors, we have developed a 3D-printed piezoresistive MEMS accelerometer and augmented the 3D printing process with a directional gold deposition process to add electrical and sensing functionality to the 3D printed MEMS structure (Figure 1) [6], [7]. The accelerometer features a responsivity of 11 ppm/g with a designed resonant frequency of 1.775 kHz, comparable with conventional MEMS accelerometers. Importantly, the total time to fabricate each device was shorter than 2.5 hours. This contrasts with the development and fabrication of conventional MEMS accelerometers, where each manufacturing iteration during development can easily take several months.

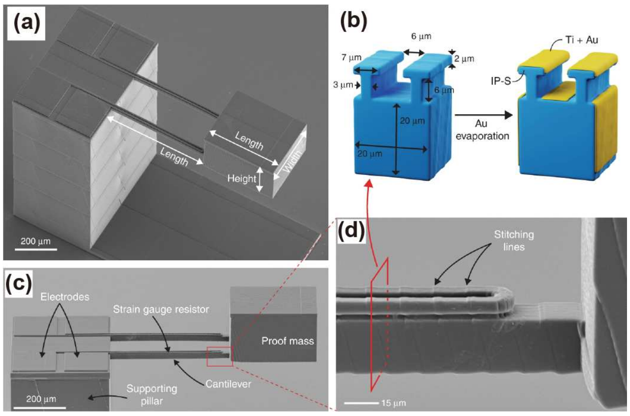

Figure 1: 3D-printed functional MEMS accelerometer. (a) Perspective SEM image of the accelerometer. (b) Schematics of the spring design to facilitate the deposition of the piezoresistive transducers. (c) Side-view SEM image of the accelerometer. (d) Enlarged SEM image of a spring of the accelerometer [6].

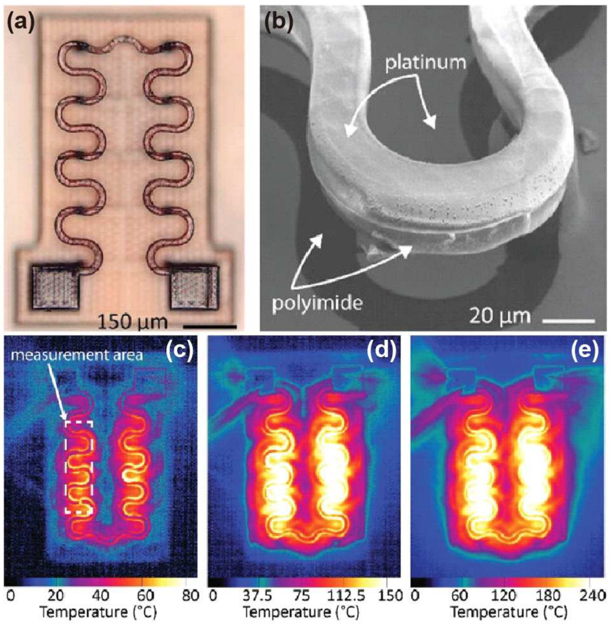

Figure 2: 3D-printed polyimide micro-hotplate. (a) Top-view optical microscope image of the micro-hotplate. (b) Enlarged SEM image of the meander wire of the micro-hotplate. (c)-(e) Thermal infrared images of the micro-hotplate operating at applied currents of 10 mA, 16 mA, and 20 mA, respectively [8].

As another example, MEMS actuators have been widely used to control specific parameters in their environment, such as temperature or the phase or amplitude of light. To demonstrate the potential of micro 3D printing for fabricating MEMS actuators, our group has 3D printed micro-hotplates consisting of a suspended meander that reduces thermal losses through heat conduction to the substrate [8]. To enable high operation temperature of the micro-hotplate, we developed a protocol for 3D printing of polyimide using multiphoton lithography. Polyimide is an organic polymer featuring outstanding thermal resistance. Using this approach in combination with directional metal deposition to provide electrical functionality, we successfully realized 3D printed polyimide micro-hotplates operating at temperatures above 300 °C (Figure 2).

MEMS components also hold promise for medical applications such as drug delivery, and the capability to fabricate complex 3D geometries offered by 3D printing using multiphoton lithography is valuable for realizing functional medical devices like spray nozzles [9] and microneedles [10]. Microscopic swirl nozzles with channel widths in the tens of micron range are useful for aerosolizing drugs in portable inhalers. Furthermore, micron-sharp microneedles can now be fabricated not only as planar arrays, but also in a spherical, entire 3D configuration, forming needle-bearing microspheres that can be applied to the skin by rubbing (Figure 3) [11]. This geometrical arrangement enables such microspheres to roll on the skin, yielding very efficient penetration, and resulting in thousands of micropores in the skin just by applying a few tens of such particles. The nanoscale resolution of 3D printing by multiphoton lithography is crucial for obtaining the sharpness of the needles, which enables the comparably soft polymers to reliably penetrate the skin with imperceptible force. Such innovative needle devices can only be manufactured due to the unique blend of nanoscale resolution, complex geometry, and appreciable printing speeds offered by 3D printing using multiphoton lithography.

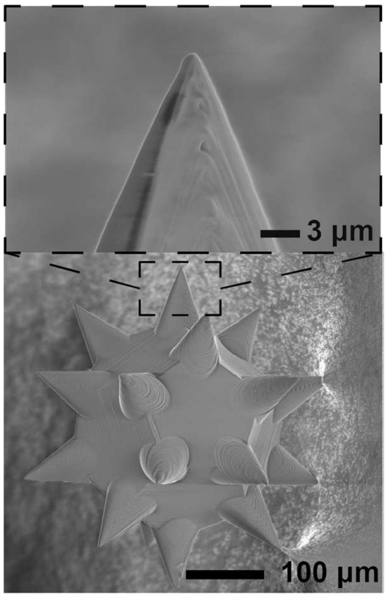

Figure 3: SEM images of a 3D-printed microneedle sphere using multiphoton lithography.

3D-PRINTED OPTICAL MEMS DEVICES

Optical MEMS devices have also been realized using 3D printing by multiphoton lithography, targeted at micro-optics applications, such as beam shaping, imaging, telecommunications, and sensing. In contrast to traditional semiconductor manufacturing technologies, 3D printing allows the fabrication of freeform 3D structures with nanoscale precision, offering enhanced design freedom, improved functionality, and greater integration flexibility. This can be used to augment optical components such as image sensors, photonic chips, and optical fibers, by integrating 3D printed structures for added functionality.

For example, 3D printing by multiphoton lithography is especially suitable for realizing lenses and beam-shaping components, as this technology allows for precise control of curvature and geometry. This has enabled the successful demonstration of single microlenses, compound lens systems, and Fresnel zone plates [12], [13], [14]. Multi-lens objectives directly 3D printed onto a CMOS image sensor were presented for imaging applications [12]. Moreover, the potential to improve photon-extraction efficiency of single-photon sources by integrating 3D-printed lenses with quantum dots has been demonstrated [13]. Using multiphoton lithography, lenses can be 3D printed with smooth surfaces and high shape accuracy, which is critical for optimal optical performance.

As another example, 3D printing has found promising applications in fabricating efficient beam couplers for coupling laser beams between optical fibers and waveguides of photonic integrated circuits (PICs). Traditionally, the coupling to photonic integrated circuits is achieved by edge couplers or grating couplers. The former offers large bandwidth and low loss but suffers from challenging assembly and limited available input/output ports due to the need for precision alignment of fiber cores to the nanoscale end face of the on-chip waveguide on the edges of the chip. On the other hand, grating couplers allow out-of-plane coupling at arbitrary positions on chips and can be manufactured using semiconductor technologies. However, they are typically wavelength- and polarization-sensitive and feature high losses, restricting their ability to achieve broadband and efficient coupling. To address this, an approach known as photonic wire bonding (PWB) was proposed to create interconnects between lasers, photonic chips, and optical fibers [15]. Moreover, a hybrid device was proposed, composed of a 3D tapered and bent waveguide and a focusing component [16]. The tapered waveguide enabled the smooth transition of modes in an on-chip waveguide to the 3D printed waveguide, and the focusing component facilitates the collection of light in the waveguide by an external optical fiber. These innovative designs provide coupling solutions for photonic integrated circuits that are broadband and low loss.

As a further example, researchers have used 3D printing to realize optical MEMS and sensor devices on optical fiber tips. For instance, a 3D printed "castle-style" humidity sensor [17], 3D printed microturbine flow sensors [18], and highly efficient optical tweezers based on 3D printed Fresnel lenses [14] on optical fiber tips have been demonstrated.

In summary, micro 3D printing has enabled new opportunities for optical MEMS components, expanding their functionality and application range across various domains.

3D PRINTING OF SILICA GLASS DEVICES

The various demonstrations of innovative 3D-printed MEMS devices are extremely promising. However, the material selection for 3D printing of structures using multiphoton lithography has long been limited to organic polymers. While the high multiphoton crosslinking efficiency of organic polymers with specialized photo-initiators is highly beneficial for the multiphoton lithography process, the material properties of these polymers are not optimal for many MEMS applications. Therefore, there has been a strong demand for high-performance materials compatible with 3D printing by multiphoton lithography. Among others, silica glass has attracted considerable interest due to its outstanding mechanical strength, optical transparency, durability, and thermal and chemical stability, with interesting opportunities for mechanical and optical MEMS components.

Micro 3D printing of nanoparticle-loaded organic photoresists with subsequent high-temperature sintering to obtain silica glass has been demonstrated recently [19]. This approach is achieved by dispersing discrete silica nanoparticles in an organic multiphoton lithography photoresist. The formed composite was slurry-like and carefully tuned to feature the transparency, viscosity, and homogeneity required for MPL. The composite was first patterned by femtosecond laser 3D direct writing and developed in solvents. The as-printed structures comprise organic polymers embedded with silica nanoparticles. Afterwards, the structures underwent high-temperature thermal postprocessing for pyrolysis and sintering up to 1100 °C to remove the organics and form solid silica glass. However, the thermal postprocessing causes significant deformation (15% linear shrinkage) of the 3D-printed structures, limiting the design freedom. Moreover, the elevated sintering temperatures severely restrict the application and integration flexibility of this approach.

To circumvent the need for sintering at extremely high temperatures, several particle-free organic-inorganic photoresists were proposed. Polyhedral oligomeric silsesquioxane (POSS) and acrylic groups were used to form an organic-inorganic multiphoton lithography photoresist [20]. Upon laser exposure, the silicon-oxygen cores of POSS molecules are crosslinked with each other through the acrylic groups to form a continuous organic-inorganic network. The hybrid network material can then be converted to solid silica glass using heat treatment at 650 °C after development. Moreover, another group developed a photochemical process that enables converting polydimethylsiloxane (PDMS) into silica glass using deep ultraviolet (DUV) irradiation in an ozone environment at 220 °C [21]. They used this process and a commercial PDMS multiphoton lithography photoresist to realize 3D silica structures. However, those approaches still involve photoresists containing organics that must be removed after laser direct writing. Thus, they inherently require postprocessing (e.g., heat treatment at 650 °C or DUV-ozone exposure) incompatible with common structural or functional materials used in MEMS and microelectronics. In addition, the associated structural deformation (>24% linear shrinkage) limits the 3D design freedom and the precise alignment between printed components.

To develop a postprocessing-free multiphoton lithography process for silica glass with negligible material shrinkage, our group has investigated the possibility of directly converting a completely inorganic material to solid silica glass with femtosecond laser exposure. Hydrogen silsesquioxane (HSQ) appeared to be a promising candidate since it has a silica-like composition ($HSiO_{1.5}$)

and is a well-known high-resolution electron beam resists without organic additives. We recently demonstrated that HSQ can be crosslinked using only femtosecond laser exposure [22]. Taking advantage of this observation, we achieved postprocessing-free 3D printing of solid silica glass with nanoscale resolution by multiphoton lithography (Figure 4(a)). The as-printed glass is solid, amorphous, and optically transparent. While a high content of 4-membered silicon-oxygen rings and photoluminescence was observed in the as-printed glass, its optical performance is suitable for photonic applications, as we showed with a 3D-printed on-chip optical resonator with out-of-plane bus waveguides (Figure 4(b)-(c)).

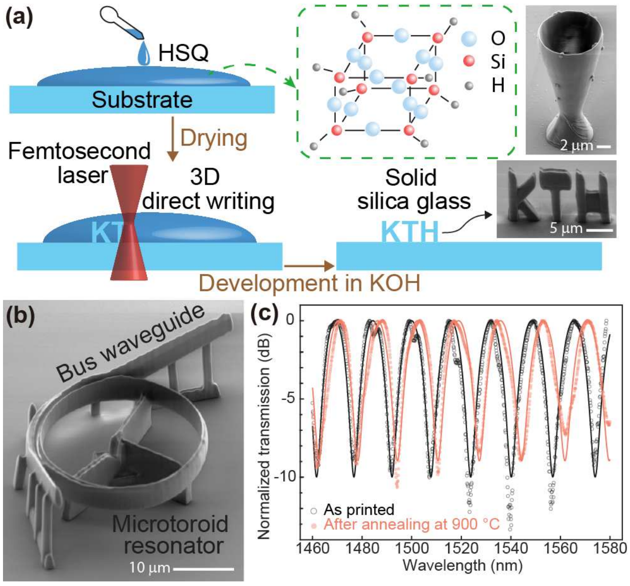

Figure 4: Postprocessing-free nanoscale 3D printing of solid silica glass using multiphoton lithography. (a) Schematic process flow with the insets showing the chemical structure of the raw material HSQ and SEM images of examples of printed structures. (b) SEM image of a 3D-printed optical MEMS comprising a microtoroid resonator and an out-of-plane bus waveguide for coupling. (c) Measured transmission spectra of the resonator in (b) without annealing and after annealing at 900 °C [22].

Furthermore, we developed an approach for efficient 3D printing of hierarchical glass structures [23] based on our observation that crosslinking of HSQ and the formation of polarization-dependent self-organized nanogratings commonly observed in bulk glass materials can simultaneously occur in HSQ in one femtosecond laser exposure (Figure 5(a)-(b)). Hierarchical structures possess unique functionalities with promising applications in photonics, energy storage, and mechanical metamaterials. We demonstrated the application of our approach by 3D printing electrodes for high-rate micro-supercapacitors with large surface areas and internal open channels beneficial for ion transport (Figure 5(c)).

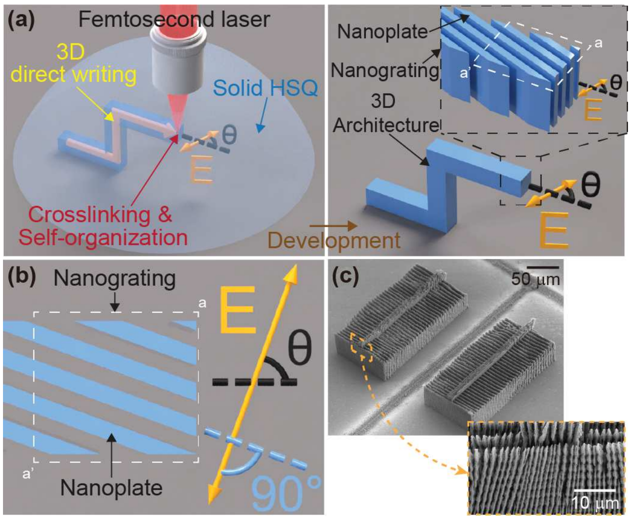

Figure 5: 3D printing of hierarchical structures made of inorganic silicon-rich glass. (a) Schematic process flow. (b) Enlarged illustration of the self-organized nanoplates in 3D-printed architecture shows that their extending direction is always perpendicular to the laser polarization. (c) SEM image of a 3D-printed micro-supercapacitor [23].

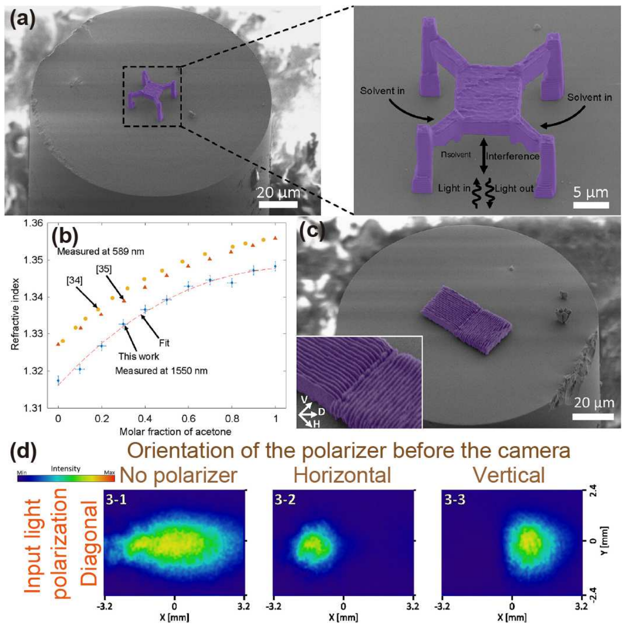

Figure 6: 3D-printed optical MEMS made of glass on tips of optical fibers. (a) SEM image of a suspended plate aligned to the fiber core, serving as a refractive index sensor. (b) Measured refractive index of acetone-methanol mixture with varying concentrations using the sensor in (a). (c) SEM image of a polarization beam splitter fabricated using the approach shown in Figure 5. (d) Output beam profiles of the device in (c) recorded by a camera, demonstrating successful splitting of the fiber input light with a polarization diagonal to the nanograting into two beams with horizontal and vertical polarizations, respectively [24].

To demonstrate the utility of our glass printing approach for optical applications, we 3D printed micro-optic devices on the tips of optical fibers [24], which would be challenging for alternative methods since the required high-temperature or photochemical postprocessing harms the optical fibers. We fabricated a refractive index sensor for measuring solvent concentrations (Figure 6(a)-(b)) and a polarization beam splitter for beam shaping (Figure 6(c)-(d)). Moreover, we proposed a process that enables selective functionalization of the 3D-printed glass by generating silicon nanocrystals in pre-defined regions [25]. This process takes advantage of our observation that additional annealing can lead to the generation of silicon nanocrystals in pristine HSQ but not in laser-crosslinked HSQ. Thus, by intentionally leaving the regions to be functionalized unexposed to the laser during direct writing, silicon nanocrystals can form in those regions in the 3D-printed glass after annealing at temperatures above 900 °C. Silicon nanocrystals are useful for various applications, including light-emitting devices, nonlinear optics, and sensors.

In summary, various approaches have been proposed recently to 3D print silica glass with its superior properties and with nanoscale resolution. Yet, for the proposed approaches using inorganic-organic composites, the negative effects of the required postprocessing at elevated temperatures or with aggressive photochemical exposure must be mitigated to improve their applicability and integration flexibility. On the other hand, to further improve our approach using inorganic HSQ without the need for organic additives and postprocessing, a deeper understanding of the multiphoton absorption process and resulting reactions in the HSQ is needed.

OUTLOOK AND CONCLUSIONS

3D printing of structures nanoscale resolution made available by multiphoton lithography has inspired and enabled the realization of innovative 3D MEMS devices, including accelerometers, medical microneedles, microlenses and optical couplers. Recent efforts have also expanded the available materials that can be 3D printed, from organic polymers to inorganic glasses, offering enhanced stability and performance. Despite these advances, further exploration of both fundamental and industrial aspects is essential to fully unlock the potential offered by 3D printing of functional MEMS components. First, there is an opportunity in shifting the design paradigm of MEMS, from the frame set by traditional semiconductor manufacturing constraints, to one that takes full advantage of the 3D design freedom of 3D printing for enhancing device functionality. This shift could be guided by developing innovative device designs and establishing corresponding design guidelines. Moreover, a key advantage of micro 3D printing is that the start-up cost is considerably lower than that of semiconductor manufacturing approaches. The start-up cost includes the time and resources required to optimize the design of a particular product and develop a corresponding manufacturing procedure, which does not scale with production volume. Semiconductor manufacturing technologies are, thus, not cost-effective for MEMS devices in small to medium volumes, up to thousands of units per year. Micro 3D printing, by contrast, offers a cost-effective solution for such applications, creating opportunities for industrial breakthroughs in high-performance MEMS production. For example, commercial high-speed multiphoton lithography 3D printers today are sufficiently fast to print from tens to hundreds of microstructures per day, depending on device complexity. This means that the cost per printed device could come down to only a few US$ and open the door for addressing a broader range of applications that previously were not possible to address economically using conventional semiconductor manufacturing. However, to 3D print functional MEMS components with competitive performance across various applications, the incorporation of a wider range of materials into 3D printed structures is essential. The significance of material diversity is evident in the recent successful demonstrations of 3D-printed silica glass components. Beyond expanding the palette of printable materials, developing novel strategies to selectively functionalize these materials—such as through doping or deposition—to obtain transduction and electrical functionalities, will play a crucial role in establishing a strong foundation for enabling new types of MEMS devices and addressing new applications.

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