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Three-dimensional direct lithography of stable quantum dots in hybrid glass

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Abstract

Semiconductor quantum dots (QDs), as high-performance materials, play an essential role in contemporary industry, mainly due to their high photoluminescent quantum yield, wide absorption characteristics, and size-dependent light emission. It is essential to construct well-defined micro-/nano- structures using QDs as building blocks for micro-optic applications. However, the fabrication of stable QDs with designed functional structures has long been challenging. Here, we propose a strategy for three-dimensional direct lithography of desired QDs within a hybrid medium with specific protection properties. The acrylate-functionalized hybrid precursors enable local crosslinking through ultrafast laser-induced multiphoton absorption, achieving sub-100 nm resolution surpassing the diffraction limit. The printed micro-/nano- structures possess thermal stability up to 600 °C, which can be transformed to inorganic architectures with a volume shrinkage. Due to the encapsulated QDs within the densely silicon-oxygen molecular networks, the functional structures demonstrate good stability against ultraviolet irradiation, corrosive solutions, and elevated temperatures. Based on hybrid 3D nanolithography, bicolor multilayer micro-/nano- structures are manufactured for applications in 3D data storage and optical information encryption. This research presents an effective strategy for the fabrication of desired QD micro-/nano- structures, supporting the development of stable functional device applications.

Supplementary material for this article is available online

Keywords: ultrafast laser, multiphoton absorption, nanolithography, stable QDs

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1. Introduction

Semiconductor quantum dots (QDs) represent highly promising materials for applications in light-emitting devices, photodetectors, and solar cells, primarily due to their exceptional electronic and optical properties [1–6]. The electronic properties of QDs are influenced by quantum effects, enabling precise control over emission and absorption characteristics through manipulating the semiconductor size [7]. However, utilizing QDs as foundational elements for micro-/nano- engineering requires advanced techniques for assembling them into precise structures [8]. The conventional photolithography approach encounters several challenges in fabricating functional micro-/nano- structures, such as the requirement for customized masks and intricate procedures [9]. Furthermore, this technique is generally inadequate for manufacturing three-dimensional (3D) ultrafine structures, thus limiting its applicability for further advancements [10, 11]. One potential strategy is to employ colloidal nanocrystals with varied compositions and strong solution processability as the core materials for 3D printing [12]. Colloidal nanocrystals can be ejected from a micronozzle using inkjet technology, and subsequently assembled into 3D microstructures through the binding forces of van der Waals interactions [13, 14]. However, the nozzle size limits the printing resolution, and the relatively weak interparticle forces may not adequately support the creation of intricate 3D architectures. Thus, it is essential to develop a strategy for fabricating 3D stable QD functional structures with high resolution.

3D laser printing provides an innovative method for manufacturing, enabling the maskless fabrication of diverse structures with nanoscale resolution [15–20]. Specifically, it imparts unique physical, or chemical properties to the printed structures, which are not typically observed at the macroscopic scale [21]. The challenge lies in finding reliable methods to bind the QDs together. Depending only on the relatively weak van der Waals interactions between nanocrystals often results in insufficient stable structures. The nanocrystals can be bonded into 3D architectures using surface ligands or photocurable resins [22]. Through ligand designing, the combination of 3D printing and chemical crosslinking can be achieved based on detachment and rebinding of surface ligands, thereby enabling semiconductor nanocrystal lithography for free-form optoelectronic devices [23]. Moreover, nonspecific interactions between nanocrystals via native ligands, facilitated by photoinduced nitrene radicals, can potentially overcome material constraints [24]. Ligand-based QDs offer significant advantages in terms of functional diversity. In the absence of an additional medium for encapsulation or cross-linking of long-chain ligands for protection, these materials face challenges in withstanding harsh environments without subsequent processing. Moreover, they can complicate efforts to prevent unfavorable interactions, such as anion exchange caused by physical contact [22]. When utilizing polymer-based QDs, where the nanocrystals are either physically incorporated into or chemically attached to photocurable resins [25–29], this composite material can be tailored to form 3D architectures. Polymer-encapsulated QDs offer a degree of protection and process compatibility. However, excessive polymer thickness can pose challenges in enhancing patterning accuracy. Additionally, a high organic content in the material may degrade the intrinsic properties of QDs and fail to provide effective protection in high-temperature and corrosive environments [22]. The connection between these two materials is not just a matter of substitution, but each is ideal for application scenarios. Thus, the question arises: can we effectively integrate the stability and functionality of printed 3D architectures? The 3D lithography of nanocrystals in glass demonstrates remarkable ability to control the composition of materials, with the glass matrix exhibiting outstanding protective properties [30–33]. In addition, the fabrication of luminescent glass via 3D printing with tailored emission color distribution was demonstrated [34]. Inspired by this, the integration of 3D laser printing with hybrid matrix encapsulation may offer a solution to these challenges.

This study presents a strategy for 3D fabrication of stable QDs within a hybrid matrix using ultrafast laser multiphoton nanolithography. The acrylate-functionalized hybrid precursor is selected as an encapsulated matrix, and the homogeneous distribution of the QDs in the matrix is achieved through surface ligand exchange. The precursor-encapsulated QDs can be locally crosslinked through a nonlinear absorption process with nanoscale resolution. The formation process of stable QD structures has been unveiled and relies on the ultrafast laser-induced multiphoton effect. The as-printed structures possess thermal stability, which can be transformed to high-quality inorganic substances. It demonstrated that the fabricated QDs encapsulated by the dielectric exhibit high stability under various harsh conditions, which can be used for optical information encryption applications.

2. Results and discussion

2.1. Concept of ultrafast laser 3D direct lithography of stable QD structures

Polymer-based QD serves as the core material in ultrafast laser direct photolithography, embodying a novel composite with photosensitive attributes. The dual components of QD/Polymer play indispensable roles in micro-optics devices. As the primary light-emitting core, QDs contribute significantly to the high optical performance. Meanwhile, polymers serve as essential complementary materials, supplementing various functions absent in QDs and ensuring the safeguarding of their optical properties. Display devices relying on QDs frequently encounter stability challenges, resulting in processing difficulties and compromised product stability. Consequently, the primary design principles for such composites should aim to fulfill the following requirements: (1) ensuring homogeneous mixing of polymers and QDs while minimizing mutual interference to preserve the stability and optical integrity of the QDs; (2) deliberate consideration of the photo-sensitizing properties of selected polymers to enhance control over pattern fineness, facilitating the preparation of intricate micro-/nano-

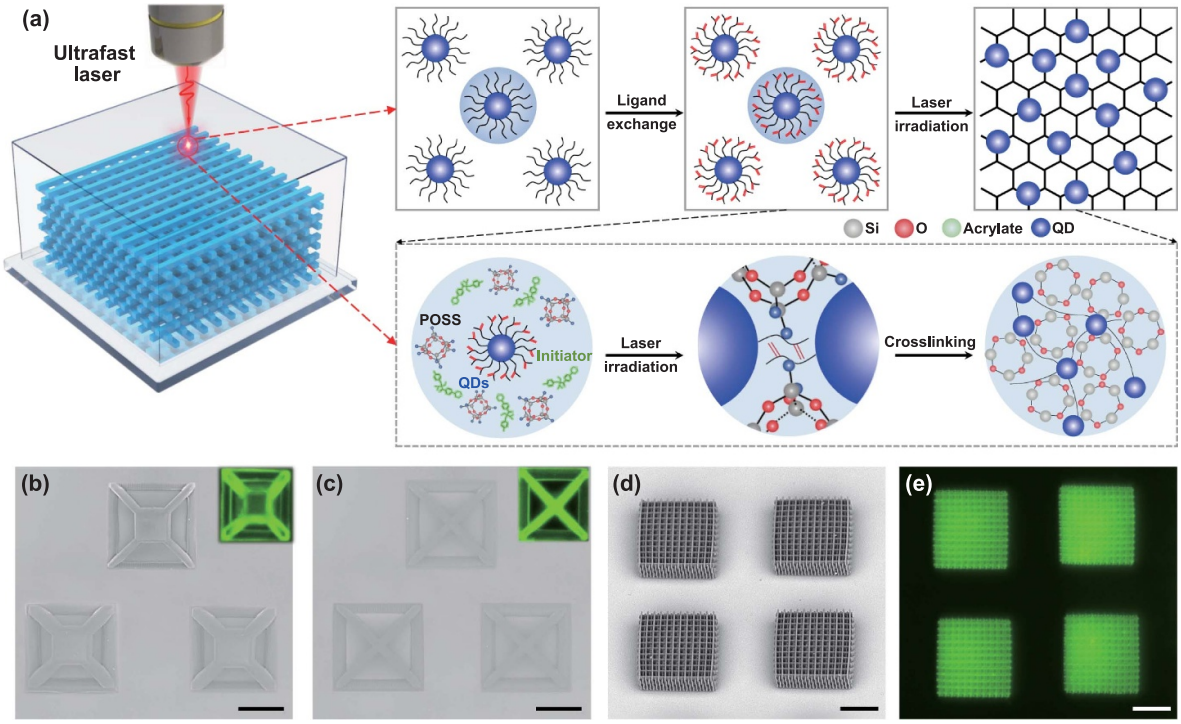


Figure 1. Ultrafast laser 3D direct nanolithography of stable QDs. (a) Scheme illustrating the 3D printing process of precursor-encapsulated QDs from a solution that contains QDs, POSS, and photoinitiator using a femtosecond laser. (b) SEM images of fabricated quadrangular platform arrays. (c) SEM images of rectangular pyramid arrays. The inset displays the fluorescent image. (d) Tilt-view SEM and (e) fluorescent images of multilayer woodpile micro-/nano- structure arrays. Scale bars: (b) and (c) 15 μm, (d) and (e) 20 μm.

structures; (3) thoughtful consideration of polymer composition to infuse the composite with specific properties, thereby yielding high-quality, feature-rich photosensitive composites. Figure 1(a) schematically illustrates the fabrication process of intricately designed QD functional structures with high resolution using ultrafast laser direct lithography. The polymer-based QD serves as a distinctive negative photoresist, comprising three vital components: QDs, a hybrid organic-inorganic precursor, and a photoinitiator. Acrylate-functionalized polyhedral oligomeric silsesquioxanes (POSS) were chosen as the encapsulating matrix. The POSS cage [35, 36], featuring silicon-oxygen frameworks, plays a crucial role in the effective protection of QDs. Unlike sol-gel resins, acrylic functional groups [37, 38], which facilitate printing in a liquid state, are essential for achieving high-quality printing. The native oleic acid-coated red- and green-emitting CdSe/ZnS QDs were modified through surface ligand exchange with carboxyethyl acrylates (CEA), resulting in the homogeneous dispersion of the QDs within the matrix (figure S1). CEA possesses a carboxylic functional group, which establishes a strong bond with zinc atoms on the QD surface, along with a methacrylate group that can co-polymerize with POSS. Furthermore, both CEA and POSS are ester compounds with similar structures, enhancing the solubility of CEA-functionalized QDs in POSS. The chosen photoinitiator (Irgacure 369) [39] facilitated the polymerization of the acrylic groups upon exposure to ultrafast laser, which possesses efficient nonlinear absorption and radical generation properties. 3D direct nanoprinting was carried out using a home-built equipment with a 1 030 nm-wavelength femtosecond laser [40–43]. The process involved dripping resin onto a glass substrate, followed by precise focusing of a laser beam into the resin. The photoinitiator underwent multiphoton absorption within the confined focal region, causing chemical bond breaking and radical generation. These radicals initiated the crosslinking of the acrylic functional groups, converting the liquid resin into a solid structure. To fabricate the 3D structures, the laser beam was moved using galvanometer mirrors for in-plane scanning, while the position of the sample stage was adjusted along three axes. Following laser printing, a bath consisting of acetone and isopropyl alcohol in a volume ratio of 3:1 was applied for 2 min. This effectively dissolved any residual uncured resin. A variety of 3D QD micro-/nano- structures with high resolution and structural quality were manufactured, including smooth quadrangular platform arrays (figure 1(b)), rectangular pyramid arrays (figure 1(c)), linear and curved 3D structures (figure S2), and complex multilayer woodpile structures (figures 1(d) and S3) with 40 μm overall size, containing individual bars with nanoscale details. Figure 1(e) shows the fluorescent image of multilayer woodpile micro-/nano- structure arrays, revealing the homogeneous distribution of all constituents. Overall, the stable QDs with high structural quality and precise size scale can be fabricated through ultrafast laser 3D direct lithography.

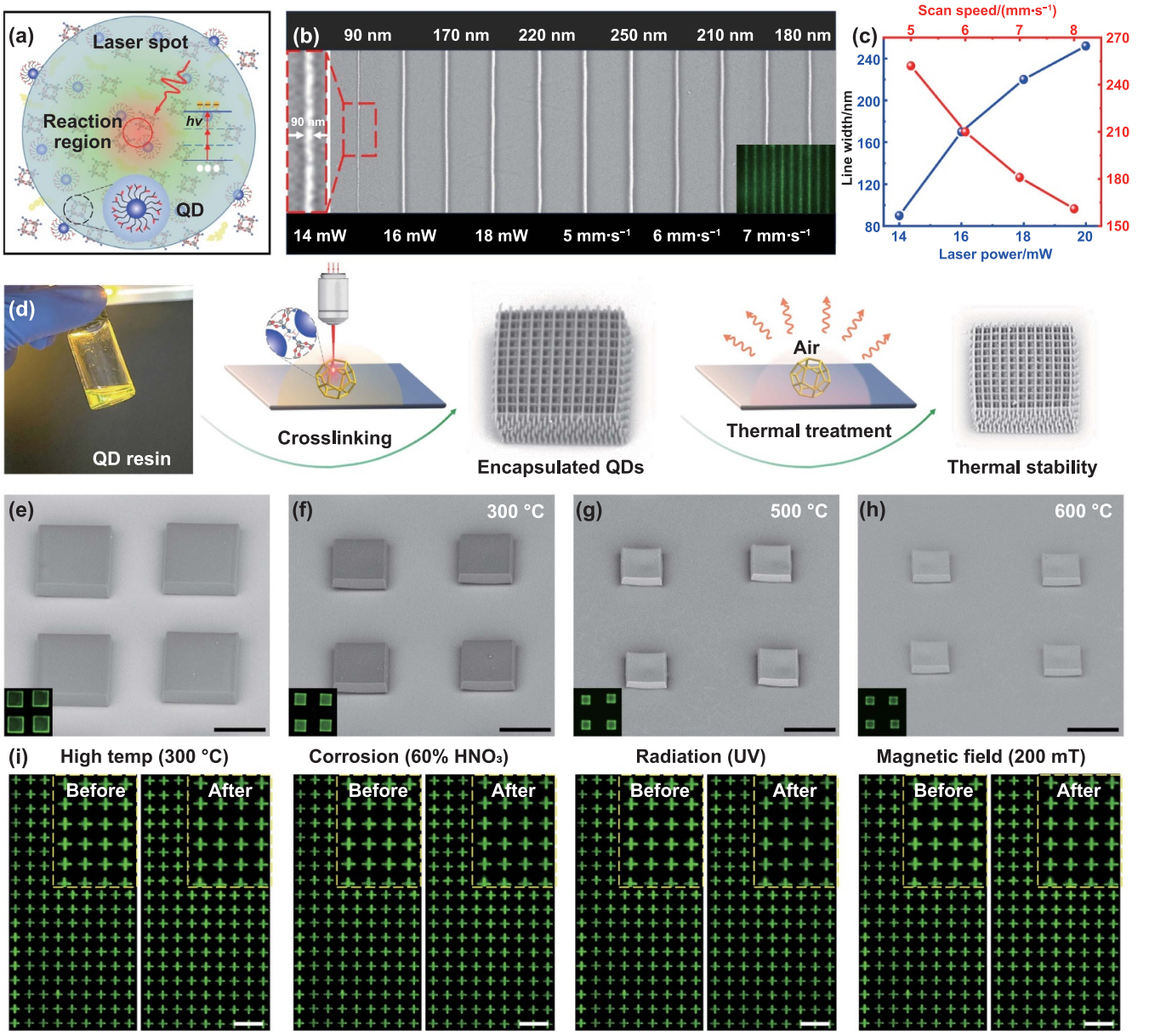


Figure 2. The formation process and structural properties of QDs within a hybrid matrix by ultrafast laser lithography. (a) Illustration of printed structures with sub-diffraction resolution by ultrafast laser-induced nonlinear effect. The blue circle denotes the laser focus spot. The inset displays the structure of QDs. (b) SEM image of QD nanowires manufactured by multiphoton lithography with various laser power and scan speed. Inset is the fluorescent image. (c) Printed linewidth variation with scan speed and laser power. The laser power was kept at 20 mW for the scan speed series, and the scan speed was fixed at 5 mm·s^{-1} for the laser power series. (d) Schematic of the printing and thermal treatment process of QD-loaded acrylate-functionalized POSS resin. (e) Tilt-view SEM image of the printed cuboid structure before heat treatment. Tilt-view SEM image of the printed cuboid structure calcinated at (f) 300 °C, (g) 500 °C and (h) 600 °C. Inset is the fluorescent image. (i) Stability characterization of encapsulated QDs under various harsh conditions, including high temperatures, strong acids, magnetic fields, and UV radiation. Scale bars: (e)–(h) 20 μm, (i) 30 μm.

2.2. Formation process and structural properties of QDs fabricated by ultrafast laser

The ultrafast laser 3D nanolithography of QD structures with nanoscale resolution has been demonstrated, leveraging the threshold effect inherent in nonlinear photoreactions [15, 44]. This effect exhibits a pronounced nonlinear relationship with femtosecond laser fluence as intensity nears the threshold. As concurrently absorbed photons increase, the effective intensity profile becomes progressively narrower. Precise modulation of laser fluence enables the generation of structural features surpassing the optical diffraction limit, achieved by ensuring that only part of the focal spot exceeds the polymerization threshold (figure 2(a)). Figure 2(b) shows an SEM image of QD nanowires manufactured by multiphoton lithography. Through meticulous control of laser power and scan speed (figure 2(c)), a QD nanowire measuring 90 nm was achieved, corresponding to λ/12 of the 1 030 nm wavelength. Under ultrafast laser irradiation, the photoinitiator situated at the central region of the laser spot experiences multiphoton

absorption. This results in the breaking of chemical bonds and the generation of radicals. Subsequently, these radicals initiate the transformation of acrylic-functional POSS molecules from their cage configuration into a network state by forming C-C bonds between adjacent POSS molecules. The crosslinking of POSS primarily occurs at the central region of the laser spot, while sub-threshold irradiation at the periphery leads to the emergence of POSS oligomers. Consequently, the central region yields glass-like characteristics upon development, creating sub-diffraction structures through the threshold effect. Numerous micro-/nano- structures were fabricated to illustrate the versatility of ultrafast laser multiphoton lithography, such as QD volumetric 3D structures (figures S4 and S5). To investigate the structural properties of the QDs encapsulated within a hybrid matrix fabricated by ultrafast laser, a controlled thermal process in an air environment was conducted (figure 2(d)). The evolution process of as-printed structures under thermal treatment at increasing temperatures was investigated (figures 2(e)–(h)). Upon heat treatment, crosslinked POSS could undergo thermo-oxidative degradation, forming peroxide groups, random chain scission, and releasing compounds such as carbon dioxide, water, and hydrocarbons [45, 46]. The applied temperature initiates the decomposition and volatilization of organic compounds, while atmospheric oxygen aids in the elimination of residual carbon. This thermal process facilitates the transformation of the initially printed structures into a glass phase according to the previous work [47]. Dimensional analyses conducted at progressively elevated temperatures, ranging from the initial as-printed state to as high as 600 °C, unveiled a consistent contraction of 36% across the printed structures during the thermal conversion process (figure S6), and their photoluminescent properties were well-preserved after thermal treatment (figure S7). Given that the QDs are encapsulated within the densely packed continuous silicon-oxygen molecular networks, we anticipate high stability in the fabricated micro-/nano- structures. The cross-structure array (figure S8) was subjected to various harsh conditions (figure 2(i)), including high temperature (300 °C, 2 h), strong acid corrosion (60% HNO_3, 12 h), UV irradiation (20 $W{\cdot}cm^{-2}$), and a magnetic field (200 mT). The precise geometric integrity of the printed structure was maintained after these treatments.

2.3. Ultrafast laser heterogeneous lithography of QD micro-/nano- structures

The heterogeneous printing of various QDs into 3D micro-/nano- structures was demonstrated (figure 3(a)), enabling the tuning of emission color through QD mixing. Figure 3(b) shows the printing process and the fluorescent images of distinct sections. In a "Taiji" diagram, structures on the left were printed using red-emitting QDs, while those on the right utilized green-emitting QDs. By mixing green- and red-emitting QDs as feedstock, the outline of the "Taiji" diagram was printed, emitting yellow light. The optical and SEM images of the printed "Taiji" diagram are shown in figure S9. Furthermore, utilizing various QDs, the letters "NANO", "GLASS" (figures 3(c) and S10), and "SZU" (figures S11 and S12) were designed and printed. Figures 3(d) and (e) present the original design, SEM, and fluorescent images of the "S"-shaped composite pattern. Initially, nine cubes of red-emitting QDs were printed, followed by the connection through drawing the "S" pattern using green-emitting QDs on top. The remarkable overlap between the design and the fluorescent image further demonstrates the high precision of the method. Heterogeneous 3D printing plays a crucial role in fabricating multifunctional optoelectronic devices, including multicolor 3D displays in free space. As shown in figures 3(f) and (g), laser direct lithography technology was utilized to inscribe 3D optical information into different layers of the inorganic matrix, enabling observation of the "GR" and "COF" letters in distinct layers (figure S13). The encapsulated QDs not only demonstrate the capability of 3D data storage but also present a potential for information encryption.

2.4. Optical information encryption applications of ultrafast laser-fabricated QD micro-/nano- structures

The strategy for ultrafast laser lithography can be used to realize the 3D direct writing of QD functional micro-/nano-structures for applications in optical information encryption. Figure 4(a) shows the schematic of the optical information writing and readout, and the fabricated monochromatic QD patterns were presented (figures S14 and S15). Figure 4(b) shows the optical and fluorescent images of the two-dimensional (QR) code pattern, printed utilizing bicolor monolayer QDs. The printing process is detailed in figure S16. This QR code comprises two segments: green-emitting QDs on the top and red-emitting QDs on the bottom. The luminescent pattern becomes apparent under 365 nm UV excitation, enabling information data storage within the QR code pattern. The reading out of information is facilitated through intelligent devices, as demonstrated by accessing website information. We further used the QDs to fabricate anticounterfeit patterns by multilayer printing. Two types of anticounterfeit information were designed, and the different QDs were employed to print on overlapping areas. The printed multilayer anticounterfeit patterns are indistinguishable via optical microscopy. Due to the narrow emission spectra of QDs and the corresponding bandpass filters, a minimal area can accommodate a large amount of information, which has immense promise for applications in the field of anticounterfeiting. Figure 4(c) shows that intricate anticounterfeit patterns within a confined area can be fabricated by adjusting printing parameters, and the information contained in each layer can be distinctly revealed. Furthermore, the change in

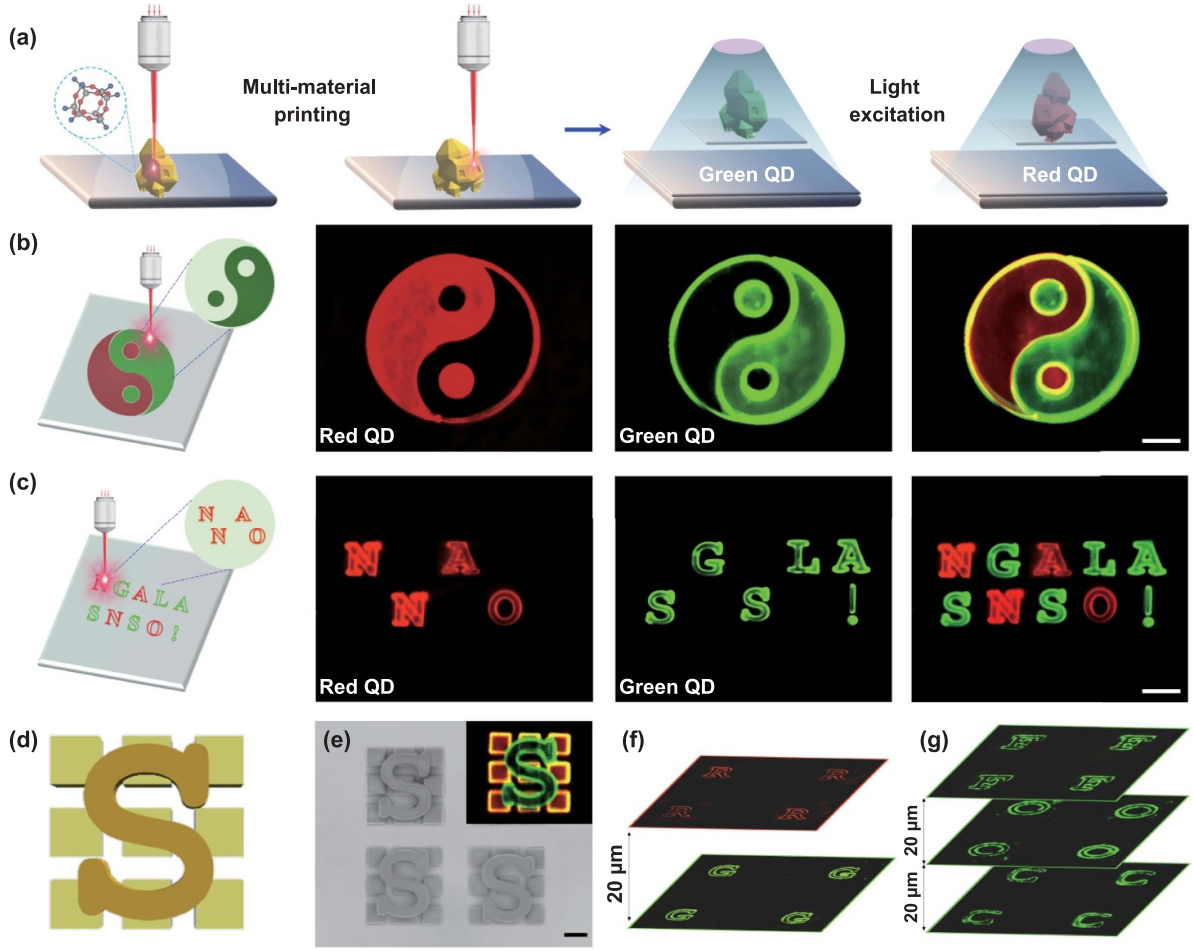


Figure 3. Heterogeneous printing and multicolor imaging. (a) Schematic of the hybrid 3D lithography of QD structures. (b) Fluorescent images of the printed "Taiji" diagram. (c) Fluorescent images of the printed English letters. Heterogeneous printing of an "S" composite pattern, with the S shape of green-emitting QDs linking the nine red-emitting QD cubes. (d) Design, (e) SEM and fluorescent images of the composite pattern. (f) and (g) 3D optical data storage. Scale bars: (b) 20 μm, (c) 10 μm, (e) 10 μm.

luminescent intensity allows for information reading, corresponding to the binary "0" and "1" states (figure 4(d)). Two-dimensional cross-structure arrays, encoded by standard computer file formats, were written to generate the binary data representing the alphabet "COFS" and the Chinese characters for "Shenzhen University". The experimental results demonstrate that the ultrafast laser-direct lithographed anticounterfeit structures possess many advantages, including high label accuracy, anticounterfeit security, and good stability.

3. Conclusion

In summary, we proposed a strategy of ultrafast laser 3D lithography for stable QDs within a hybrid matrix. The acrylate-functionalized hybrid precursors can undergo local crosslinking via ultrafast laser-induced nonlinear effects. Compared to linear absorption, the fabrication of high-quality encapsulated QDs with sub-100 nm resolution can be achieved through multiphoton absorption. The as-printed micro-/nano- structures exhibited thermal stability, and can be transformed into inorganic substances following annealing at 600 °C. The QDs demonstrate good stability even under diverse harsh conditions due to the protection from the densely packed continuous silicon-oxygen molecular networks. Bicolor multilayer QD micro-/nano- structures were constructed by ultrafast laser 3D direct lithography for applications in optical information encryption. On the other hand, there are some limitations and potential challenges for electrical applications due to the hybrid matrix encapsulation. This work advances the understanding of ultrafine QD structure fabrication and presents a strategy for developing stable functional devices for various micro-optic applications.

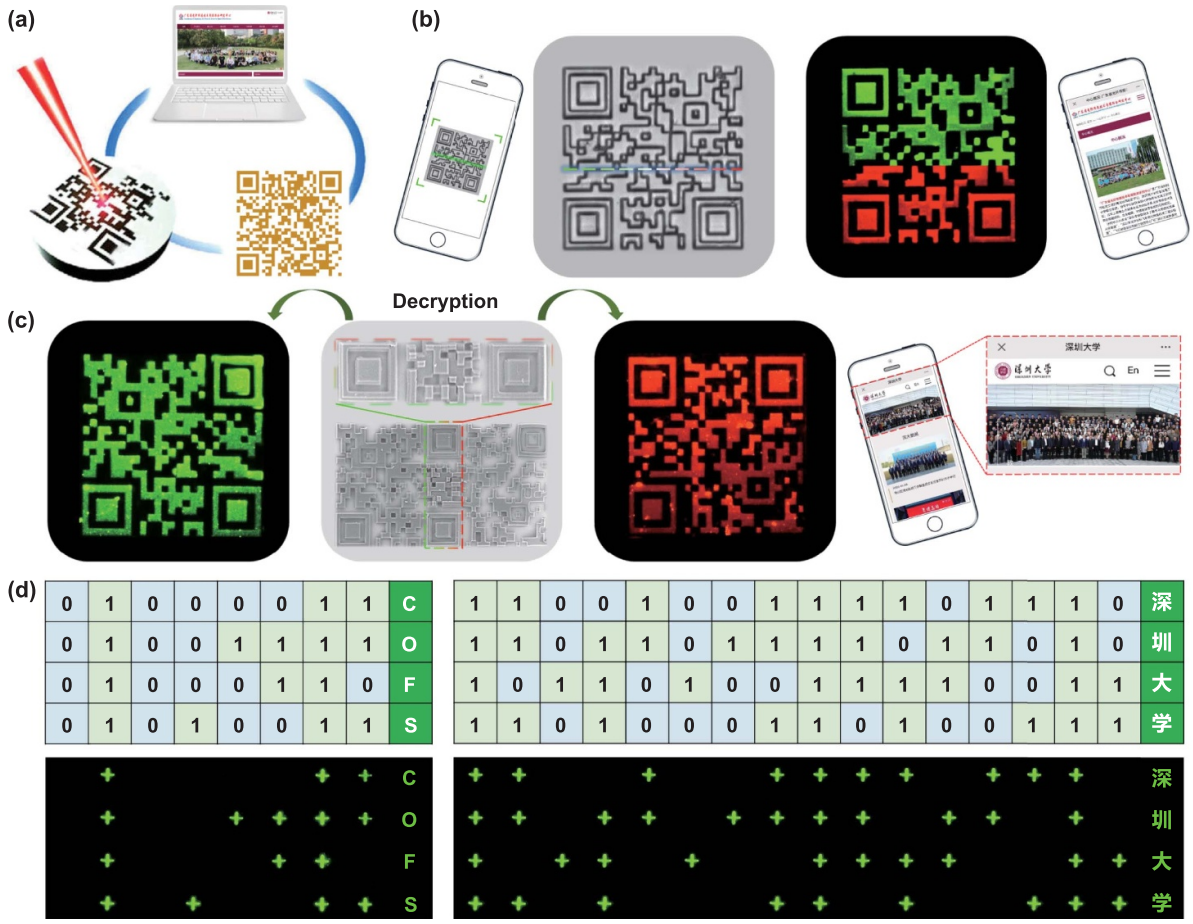


Figure 4. Multimodal information encryption utilizing ultrafast laser-fabricated QD micro-/nano- structures. (a) Schematic of the optical information writing and readout. (b) Encrypting and decoding information within the two-dimensional code pattern based on bicolor monolayer QDs. (c) Encrypting and decoding information within the two-dimensional code pattern based on bicolor multilayer QDs. (d) The "COFS" alphabet (left) and the "shen zhen da xue" Chinese characters (right) are encoded in binary format.

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Conflict of interest

The authors declare no conflicts of interest.

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References

[1] Jiang Y Z *et al* 2022 Synthesis-on-substrate of quantum dot solids *Nature* **612** 679–84
[2] García de Arquer F P, Talapin D V, Klimov V I, Arakawa Y, Bayer M and Sargent E H 2021 Semiconductor quantum dots: technological progress and future challenges *Science* **373** eaaz8541
[3] Xia C *et al* 2021 General synthesis of single-atom catalysts with high metal loading using graphene quantum dots *Nat. Chem.* **13** 887–94
[4] Wang L *et al* 2020 Full-color fluorescent carbon quantum dots *Sci. Adv.* **6** eabb6772
[5] Park S Y, Lee S, Yang J and Kang M S 2023 Patterning quantum dots via photolithography: a review *Adv. Mater.* **35** 2300546
[6] Liu M X, Yazdani N, Yarema M, Jansen M, Wood V and Sargent E H 2021 Colloidal quantum dot electronics *Nat. Electron.* **4** 548–58
[7] Bai Y, Hao M M, Ding S S, Chen P and Wang L Z 2022 Surface chemistry engineering of perovskite quantum dots: strategies, applications, and perspectives *Adv. Mater.* **34** 2105958
[8] Ball P 2023 Printing with a quantum dot matrix *Nat. Mater.* **22** 1276

[9] Fan J P and Qian L 2022 Quantum dot patterning by direct photolithography *Nat. Nanotechnol.* **17** 906–7
[10] Liu D *et al* 2022 Direct optical patterning of perovskite nanocrystals with ligand cross-linkers *Sci. Adv.* **8** eabm8433
[11] Wang Y Y, Fedin I, Zhang H and Talapin D V 2017 Direct optical lithography of functional inorganic nanomaterials *Science* **357** 385–8
[12] MacDonald E and Wicker R 2016 Multiprocess 3D printing for increasing component functionality *Science* **353** aaf2093
[13] Ahn B Y, Duoss E B, Motala M J, Guo X Y, Park S I, Xiong Y J, Yoon J, Nuzzo R G, Rogers J A and Lewis J A 2009 Omnidirectional printing of flexible, stretchable, and spanning silver microelectrodes *Science* **323** 1590–3
[14] Bae J, Lee S, Ahn J, Kim J H, Wajahat M, Chang W S, Yoon S Y, Kim J T, Seol S K and Pyo J 2020 3D-printed quantum dot nanopixels *ACS Nano* **14** 10993–1001
[15] Kawata S, Sun H B, Tanaka T and Takada K 2001 Finer features for functional microdevices *Nature* **412** 697–8
[16] Yang L *et al* 2023 Laser printed microelectronics *Nat. Commun.* **14** 1103
[17] Ouyang W Q, Xu X Y, Lu W P, Zhao N, Han F and Chen S C 2023 Ultrafast 3D nanofabrication via digital holography *Nat. Commun.* **14** 1716
[18] Liu T Q *et al* 2024 Ultrahigh-printing-speed photoresists for additive manufacturing *Nat. Nanotechnol.* **19** 51–57
[19] Han F, Gu S Y, Klimas A, Zhao N, Zhao Y X and Chen S C 2022 Three-dimensional nanofabrication via ultrafast laser patterning and kinetically regulated material assembly *Science* **378** 1325–31
[20] Saha S K, Wang D E, Nguyen V H, Chang Y N, Oakdale J S and Chen S C 2019 Scalable submicrometer additive manufacturing *Science* **366** 105–9
[21] Liu S F, Hou Z W, Lin L H, Li Z C and Sun H B 2023 3D laser nanoprinting of functional materials *Adv. Funct. Mater.* **33** 2211280
[22] Guo W S, Chen J, Ma T, Chen Z Y, Li M L, Zeng H B and Lu J 2024 Direct photolithography patterning of quantum dot-polymer *Adv. Funct. Mater.* **34** 2310338
[23] Liu S F, Hou Z W, Lin L H, Li F, Zhao Y, Li X Z, Zhang H, Fang H H, Li Z C and Sun H B 2022 3D nanoprinting of semiconductor quantum dots by photoexcitation-induced chemical bonding *Science* **377** 1112–6
[24] Li F *et al* 2023 3D printing of inorganic nanomaterials by photochemically bonding colloidal nanocrystals *Science* **381** 1468–74
[25] Yu Y, Prudnikau A, Lesnyak V and Kirchner R 2023 Quantum dots facilitate 3D two-photon laser lithography *Adv. Mater.* **35** 2211702
[26] Ingrosso C, Fakhfouri V, Striccoli M, Agostiano A, Voigt A, Gruetzner G, Curri M L and Brugger J 2007 An epoxy photoresist modified by luminescent nanocrystals for the fabrication of 3D high-aspect-ratio microstructures *Adv. Funct. Mater.* **17** 2009–17
[27] Jang J *et al* 2021 Extremely stable luminescent crosslinked perovskite nanoparticles under harsh environments over 1.5 years *Adv. Mater.* **33** 2005255
[28] Zhang P P, Yang G L, Li F, Shi J B and Zhong H Z 2022 Direct *in situ* photolithography of perovskite quantum dots based on photocatalysis of lead bromide complexes *Nat. Commun.* **13** 6713
[29] Efros A L and Brus L E 2021 Nanocrystal quantum dots: from discovery to modern development *ACS Nano* **15** 6192–210
[30] Sun K *et al* 2022 Three-dimensional direct lithography of stable perovskite nanocrystals in glass *Science* **375** 307–10
[31] Wang Z, Zhang B, Wang Z Q, Zhang J, Kazansky P G, Tan D Z and Qiu J R 2023 3D imprinting of voxel-level structural colors in lithium niobate crystal *Adv. Mater.* **35** 2303256
[32] Hu Z, Huang X J, Yang Z W, Qiu J B, Song Z G, Zhang J Y and Dong G P 2021 Reversible 3D optical data storage and information encryption in photo-modulated transparent glass medium *Light Sci. Appl.* **10** 140
[33] Huang X J, Guo Q Y, Yang D D, Xiao X D, Liu X F, Xia Z G, Fan F J, Qiu J R and Dong G P 2020 Reversible 3D laser printing of perovskite quantum dots inside a transparent medium *Nat. Photon.* **14** 82–88
[34] Ouyang M, Zhang H, Li M J, Zhang J, Gong Y Q, Huang X J, Liu X F, Qiu J R, Yang Z M and Dong G P 2023 3D printing of luminescent glass with controlled distribution of emission colors for multi-dimensional optical anti-counterfeiting *Laser Photonics Rev.* **17** 2300068
[35] Zhou D L, Li J H, Guo Q Y, Lin X, Zhang Q, Chen F, Han D and Fu Q 2021 Polyhedral oligomeric silsesquioxanes based ultralow-*k* materials: the effect of cage size *Adv. Funct. Mater.* **31** 2102074
[36] Fang G, Cao H Z, Cao L C and Duan X M 2018 Femtosecond laser direct writing of 3D silica-like microstructure from hybrid epoxy cyclohexyl POSS *Adv. Mater. Technol.* **3** 1700271
[37] Wang H *et al* 2023 Two-photon polymerization lithography for optics and photonics: fundamentals, materials, technologies, and applications *Adv. Funct. Mater.* **33** 2214211
[38] Gan Z S, Cao Y Y, Evans R A and Gu M 2013 Three-dimensional deep sub-diffraction optical beam lithography with 9 nm feature size *Nat. Commun.* **4** 2061
[39] Liaros N and Fourkas J T 2021 Methods for determining the effective order of absorption in radical multiphoton photoresists: a critical analysis *Laser Photonics Rev.* **15** 2000203
[40] Zhu D Z, Xie J W, Yan J F, He G Z and Qiao M 2023 Ultrafast laser plasmonic fabrication of nanocrystals by molecule modulation for photoresponse multifunctional structures *Adv. Mater.* **35** 2211983
[41] Zhang J, Zhu D Z, Yan J F and Wang C A 2021 Strong metal-support interactions induced by an ultrafast laser *Nat. Commun.* **12** 6665
[42] Zhu D Z, Yan J F, Xie J W, Liang Z W and Bai H L 2021 Ultrafast laser-induced atomic structure transformation of Au nanoparticles with improved surface activity *ACS Nano* **15** 13140–7
[43] Zhu D Z, Qiao M, Yan J F, Xie J W, Guo H, Deng S F, He G Z, Zhao Y Z and Luo M 2023 Three-dimensional patterning of MoS_2 with ultrafast laser *Nanoscale* **15** 14837–46
[44] Liu K L, Ding H B, Li S, Niu Y F, Zeng Y, Zhang J N, Du X and Gu Z Z 2022 3D printing colloidal crystal microstructures via sacrificial-scaffold-mediated two-photon lithography *Nat. Commun.* **13** 4563
[45] Li L G, Liang R D, Li Y J, Liu H Z and Feng S Y 2013 Hybrid thiol–ene network nanocomposites based on multi (meth) acrylate POSS *J. Colloid Interface Sci.* **406** 30–36
[46] Krongauz V V 2010 Crosslink density dependence of polymer degradation kinetics: photocrosslinked acrylates *Thermochim. Acta* **503–504** 70–84
[47] Zhu D Z *et al* 2024 Ultrafast laser 3D nanolithography of fiber-integrated silica microdevices *Nano Lett.* **24** 9734–42