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Applications of flexible and stretchable three-dimensional structures for soft electronics

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Abstract

The development of devices that can be mechanically deformed in geometrical layouts, such as flexible/stretchable devices, is important for various applications. Conventional flexible/stretchable devices have been demonstrated using two-dimensional (2D) geometry, resulting in dimensional constraints on device operations and functionality limitations. Accordingly, expanding the dimensions in which such devices can operate and acquiring unique functionality that is difficult to implement in 2D planar structures remain challenging. As a solution, the development of a flexible/stretchable device embedding a three-dimensional (3D) structure fabricated through the precise control of a 2D structure or direct construction has been attracting significant attention. Because of a significant amount of effort, several 3D material systems with distinctive engineering properties, including electrical, optical, thermal, and mechanical properties, which are difficult to occur in nature or to obtain in usual 2D material systems, have been demonstrated. Furthermore, 3D advanced material systems with flexibility and stretchability can provide additional options for developing devices with various form factors. In this review, novel fabrication methods and unprecedented physical properties of flexible/stretchable 3D material systems are reviewed through multiple application cases. In addition, we summarized the latest advances and trends in innovative applications implemented through the introduction of advanced 3D systems in various fields, including microelectromechanical systems, optoelectronics, energy devices, biomedical devices, sensors, actuators, metamaterials, and microfluidic systems.

Keywords: Flexible, stretchable, three-dimensional (3D), soft electronics

INTRODUCTION

The importance of flexible/stretchable devices in next-generation soft electronics such as emerging displays, smart sensors, wearable devices, and wireless communication devices is growing[1-4]. Accordingly, several flexible/stretchable device fabrication technologies have been reported, and these fabrication methodologies produce soft electronic devices that can not only be bent, twisted, or stretched but allow them to be freely transformed into a desired shape[5-8]. In addition to the diversity of device design, various advantages, including ultra-lightweight[9], unbreakability[10], overcoming space constraints[11], and low cost[12] can be realized, and in particular, mechanical stability against deformation caused by human motion or displacement of these devices can be achieved without deterioration in performance[13-15]. Based on the aforementioned superior characteristics, high-functional flexible/stretchable devices such as electronic skin[16], smart fabric[17], and wearable energy harvesters[18] are being developed in various fields, including microelectromechanical systems (MEMS)[19-27], optoelectronics[7,28-38], actuators[39-46] and micro-fluidic systems[47-54].

However, most of the reported flexible/stretchable devices operate with a two-dimensional (2D) planar or stacked device structure, and there are several challenges in the implementation of novel functionality and application to various fields due to the dimensional constraints of the structure. For example, devices that can detect external fields only in small spatial resolutions with one or two dimensions may have difficulty in detecting vector fields in three-dimensional (3D) space, and sensing an *in vivo* cell with a complex morphology requires a device with a 3D contact surface area. In this regard, several studies have shown that forming or embedding 3D structural components in flexible/stretchable devices can overcome the dimensional limitations of device operations as well as allow for the implementation of fundamentally new properties and functionalities that are difficult to realize with 2D structures in various application fields [Figure 1]. For example, broadband electromagnetic radiation can be achieved by constructing a geometrically reconfigurable 3D mesostructure on a soft substrate[55], allowing the narrowband resonant optical reconfigurations through the transformable optical nano-kirigami[56], and implementing frequency-selective surfaces with stable electromagnetic wave transmission performance by buckling a periodic array of Jerusalem 2D precursors[57].

In this review, we first briefly discuss representative manufacturing methods of 3D structures, and introduce the implementation of MEMS capable of unique functions or multimodal operations by rearranging 3D structures such as antennas and sensors in the second section. The third section describes light-emitting diodes (LEDs) and photodetectors, which can achieve operational stability against deformation or overcome spatial constraints by using 3D architectures. In the next section (fourth section), we introduce energy devices such as energy harvesters and batteries that can achieve high performance with high surface areas and electrochemical stability resulting from the formation of 3D structures. Then, the fifth section discusses a methodology for fabricating 3D structures that exquisitely mimic biological tissues and tiny biomedical devices that can accurately monitor the physiological properties of 3D biological systems. The sixth section covers several sensors that detect various factors such as temperature, strain, and magnetic field and achieve spatial expansion of the sensing area through 3D geometry. The seventh section introduces 3D actuators that can perform unique movements or behaviors within a 3D space in response to multiple external stimuli, and metamaterials that exhibit unique physical behaviors through elaborately designed geometries in 3D are discussed in the eighth section. In the ninth section, we cover 3D flexible/stretchable microfluidic systems obtained by introducing soft materials into the fabrication process of 3D complex networks. Finally,

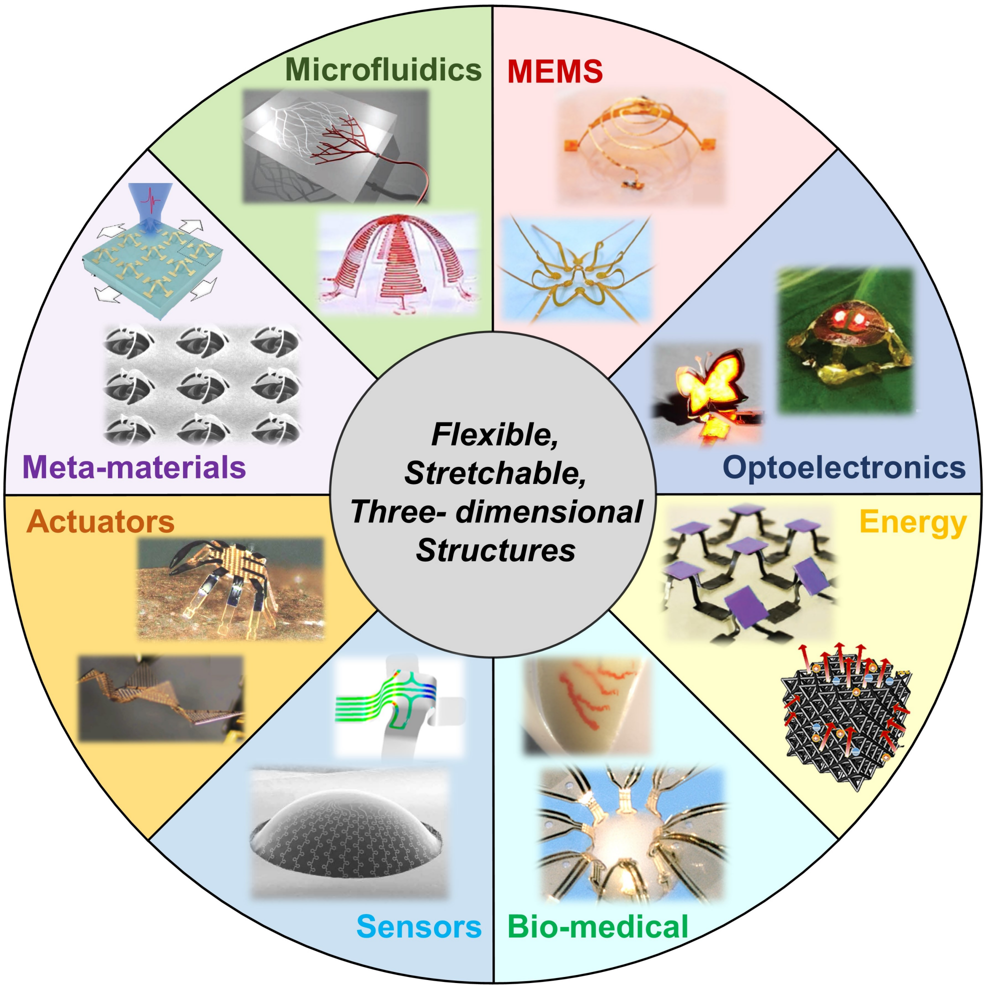

Figure 1. Diagram of the application of flexible, stretchable, 3D structures for MEMS (Top: Reproduced with permission from Ref.[147]. Copyright© 2019. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. Bottom: Reproduced with permission from Ref.[55]. Copyright© 2020. American Association for the Advancement of Science), LED & photodetector (Right: Reproduced with permission from Ref.[161]. Copyright© 2019. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. Left: Reproduced with permission from Ref.[159]. Copyright© 2021. Springer Nature), energy devices (Top: Reproduced with permission from Ref.[177]. Copyright© 2021. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. Bottom: Reproduced with permission from Ref.[174]. Copyright© 2022. American Chemical Society), biomedical devices (Top: Reproduced with permission from Ref.[191]. Copyright© 2019. American Association for the Advancement of Science. Bottom: Reproduced with permission from Ref.[196]. Copyright© 2021. American Association for the Advancement of Science), sensors (Top: Reproduced with permission from Ref.[205]. Copyright© 2019. American Chemical Society, Bottom: Reproduced with permission from Ref.[208]. Copyright© 2020. American Association for the Advancement of Science), actuators (Top: Reproduced with permission from Ref.[219]. Copyright© 2022. American Association for the Advancement of Science. Bottom: Reproduced with permission from Ref.[221]. Copyright© 2022. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim), metamaterials (Top: Reproduced with permission from Ref.[57]. Copyright© 2022. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. Bottom: Reproduced with permission from Ref.[56]. Copyright© 2021. Springer Nature), and microfluidic systems (Top: Reproduced with permission from Ref.[236]. Copyright© 2011. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. Bottom: Reproduced with permission from Ref.[237]. Copyright© 2022. American Chemical Society).

the challenges and opportunities of flexible/stretchable devices with 3D structures are discussed.

Manufacturing method for 3D structures

There is a need for innovative hardware fabrication concepts or platforms in order to realize highly functional flexible/stretchable devices composed of 3D structures with feature sizes from the micro to the macroscale. In this regard, several efforts have been made to fabricate 3D structures to create extremely high device performances or unique functionalities that cannot be achieved with existing 2D devices[58-69]. There is a method for converting a 2D structure into a 3D structure by mechanically guiding the assembly (buckling)[70-75], folding (origami)[76-78], or cutting (kirigami)[79-84] a 2D structure along a predesigned pattern, as well as directly fabricating the desired 3D structure (3D printing) [Figure 2][85-87]. The assembly processes for the aforementioned 3D structure manufacturing methods are detailed below, along with material availability, unique structural features, and design and manufacturing advantages of each method. In terms of material availability, methods such as mechanically-guided assembly, origami, and kirigami, which produce 3D structures by transforming and assembling 2D structures, can be applied to nearly all types of advanced materials, including metals, semiconductors and polymers. The 3D printing method has generally focused on conductive ink with optimized rheology and incorporates various types of materials. Furthermore, it is necessary to discuss the unique structural features of each method, which are closely related to the device's function. The mechanically-guided assembly is characterized by a deformable substrate. Origami and kirigami have foldable creases, while 3D printing has a relatively high degree of structural freedom. Next, the design and manufacturing advantages of each method are discussed. A mechanically-guided assembly could be introduced to multilayer 2D precursors to obtain a dense and complex 3D architecture with overlaid layouts and entanglement points. Both origami and kirigami methods, though primarily through kirigami's reduction in stress concentration, facilitate control of curves and provide high design flexibility. 3D printing has the advantages of programmability, scalability, and low entry barriers in the fabrication of soft electronics. By carefully applying these 3D structure manufacturing methods with unique characteristics in the right places, 3D structures have been incorporated into various application fields, such as energy-harvesting[88-95], biomedical[96-106], sensors[107-116], and metamaterials[117-121].

Mechanically-guided assembly

The mechanically-guided assembly has been studied as a precise and well-controlled 2D-3D conversion method that can extend geometry to 3D while maintaining compatibility with 2D microsystem technology. Figure 2A shows the mechanical assembly process of a 3D structure consisting of three key steps: precursor production, transfer printing, and mechanical buckling. This process begins by manufacturing 2D precursors through general lithography techniques on source wafers or other planar substrates. Selective bonding sites and sacrificial layers are formed through sputtering or deposition technologies. The 2D precursor is then transferred to a pre-stretched elastomer substrate through a transfer printing process using a polydimethylsiloxane (PDMS) stamp or water-soluble tape to induce strong covalent bonding of the contact sites. Finally, by releasing the compression applied to the elastomer substrate, which serves as a platform to provide the mechanical force needed to drive the 3D assembly, the 2D precursor is converted to a precisely-designed 3D geometry through spatial deformation, in-plane/out-of-plane conversion, and rotational motion. This assembly process is expected to produce various 3D structures with unique architecture and functions by controlling key factors that affect the assembly, such as changing the 2D layout of the precursor, adjusting the pre-strain characteristics of the assembly substrate, and patterning for selective bonding.

Origami and kirigami

Origami and kirigami, which translate to "paper folding" and "paper cutting," are methods of converting 2D flat objects into 3D structures using "folding" and "cutting" as basic processes, respectively. Although many studies do not establish a clear boundary between origami and kirigami, "folding" is a common feature of the two methodologies. These methods can modify the shapes of various materials, such as metals, polymers, hydrogels, graphene, and paper, from the macroscale to the nanoscale. As shown in Figure 2B, the origami structure is typically folded to a compressed volume compared to the initial state, while the kirigami structure has an expanded configuration from the initial state. In addition, a hybrid origami-kirigami design that combines the two concepts is emerging to realize more complex

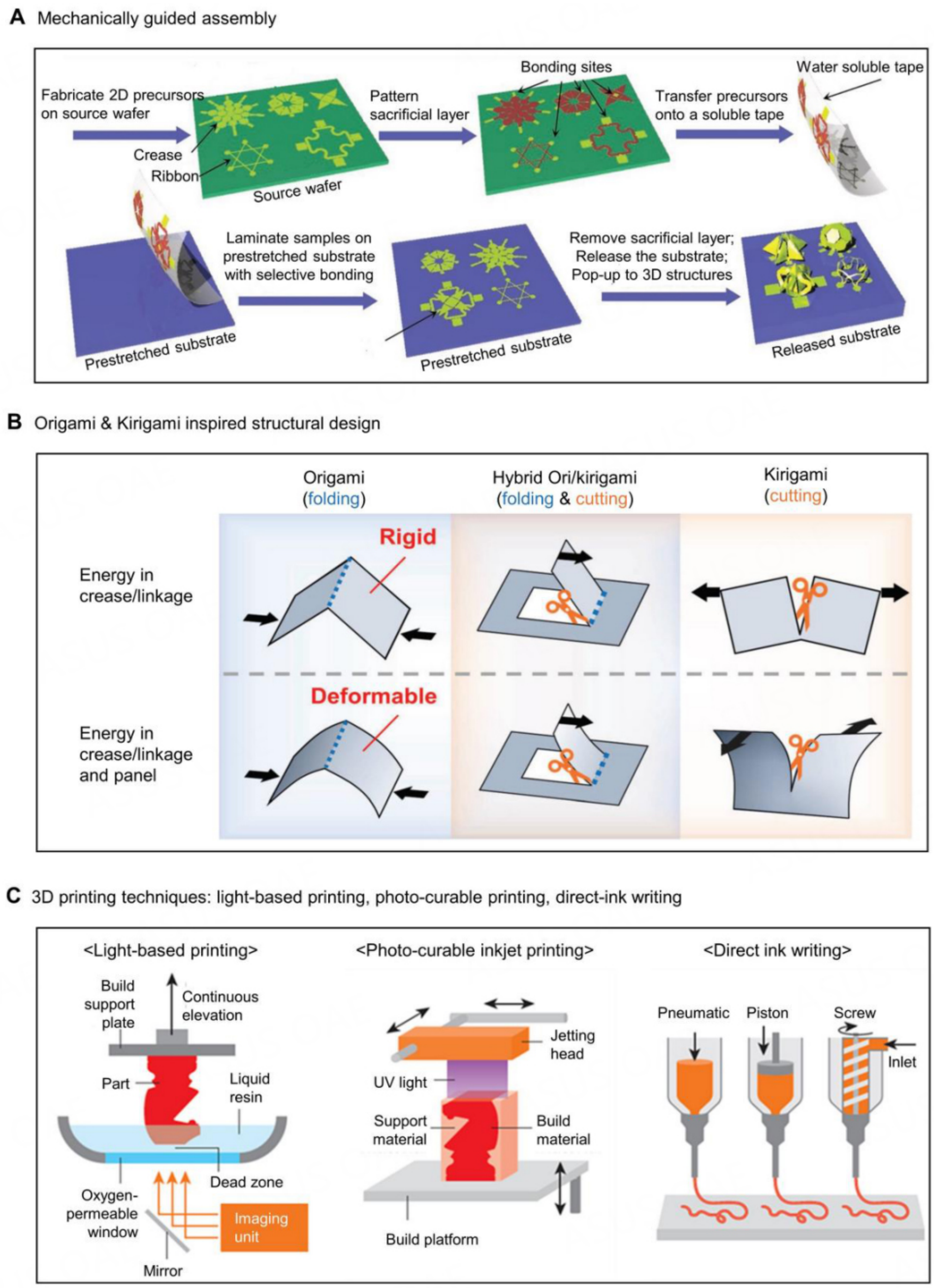

Figure 2. (A) Schematic illustration of the mechanically-guided assembly process. (Reproduced with permission from Ref.[63]. Copyright© 2019. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim); (B) structural design through origami and kirigami methods. (Reproduced with permission from Ref.[239]. Copyright© 2021. AIP Publishing); (C) light-based, photocurable material-based, and direct ink-based 3D printing (Reproduced with permission from Ref.[240]. Copyright© 2016. Springer Nature).

configurations. Both methods divide thin materials into flexible areas (i.e., a crease for origami, and a linkage for kirigami) and rigid areas (i.e., a thin panel). The panels normally remain rigid during deformation and energy is stored in the crease or linkage (as shown in the top row of Figure 2B). However, if the panel is deformable, elastic energy can be stored in both the panel and the linkage, providing more programming possibilities (as shown in the bottom row of Figure 2B). Consequently, the mechanical behavior of the structure is determined by the balance between the flexibility and rigidity of the pattern. Origami and kirigami are excellent candidates for forming a unique 3D structure by designing the energy landscape through the process of folding and cutting.

3D printing

3D printing encompasses a wide range of light- and ink-based printing technologies that enable the digital design and production of 3D objects, and mainly focuses on rapid prototyping. 3D printing typically moves the laser optics or ink-based pattern generation head to create an object layer by layer, and the pattern area consisting of resin, powder, or ink is solidified to generate a desired 3D shape during the printing process. Various 3D printing technologies have been reported[122-124], and Figure 2C shows representative examples. Light-based 3D printing technology uses light to sculpt objects through stereolithography (SLA) of photocurable resin or selective laser sintering (SLS) of polymer powder. Photocurable resin-based 3D printing technology combines ink-based printing and light-based printing into one platform, creating structures through the polymerization of photocurable resin via exposure to ultraviolet light sources. Finally, direct ink writing is a method of immediately drawing a desired shape through the direct injection of viscoelastic materials under ambient conditions. 3D printing technology is gaining attention as a suitable methodology to produce 3D structures according to user orders. Continuous development of 3D printing methods capable of high speeds, high precision, mass production, and high degrees of freedom in the printing materials are expected to produce high-performance devices for a wide range of applications, including sensors, actuators, and electronics.

Microelectromechanical systems

With the demand for the miniaturization of devices, Microelectromechanical systems (MEMS), a multifunctional component that can simultaneously perform different roles such as sensors, electronic circuits, and actuators, have made significant progress[125-127]. In particular, the integration of 2D MEMS with flexible/stretchable substrates has shown the possibility of implementing deformable soft electronic devices in various fields, including biomedical technology[128], optical devices[129], and the Internet of Things[130]. In addition to this design diversity, high-functionalities such as customizable telecommunication and frequency reconfiguration are required to expand the application area, and additional advantages can be provided by embedding geometrically complex 3D microstructures in MEMS. Thus far, several methodologies for installing electronic components in 3D complex morphology, particularly on a millimeter to micrometer scale, on flexible/stretchable boards have been proposed. Representative examples include buckling methods that transform 2D precursors into 3D structures through physical deformation[131-135] and origami/kirigami that obtains a desired shape by cutting or folding materials[136-142]. This chapter introduces various studies on the fabrication of 3D MEMS devices that can operate in multiple states/modes through mechanical reconfigurations [Figure 3].

Fu *et al.* demonstrated a reconfigurable 3D radiofrequency electromagnetic device that can be deformed in different time sequences via nonlinear mechanical buckling [Figure 3A][143]. The antennas are elevated and exposed in the working mode, and then, the reconfiguration of the system allows the coil to be hidden by the metallic support and electromagnetically shielded. Electronic components that can be switched to different states through reversible shape changes highlight their potential for use in advanced communication devices. Luan *et al.* demonstrated a double-floor helical-shaped 3D microfluidic mesostructure integrated with electronic components such as micro LEDs, heaters, thermistors, and electrodes [Figure 3B][51]. The 3D hybrid system could withstand various types of elastic deformation, including bending and twisting, through the selective bonding technique. 3D structures capable of physical deformation and endowed with electronic sensing and regulating functions can achieve systematic

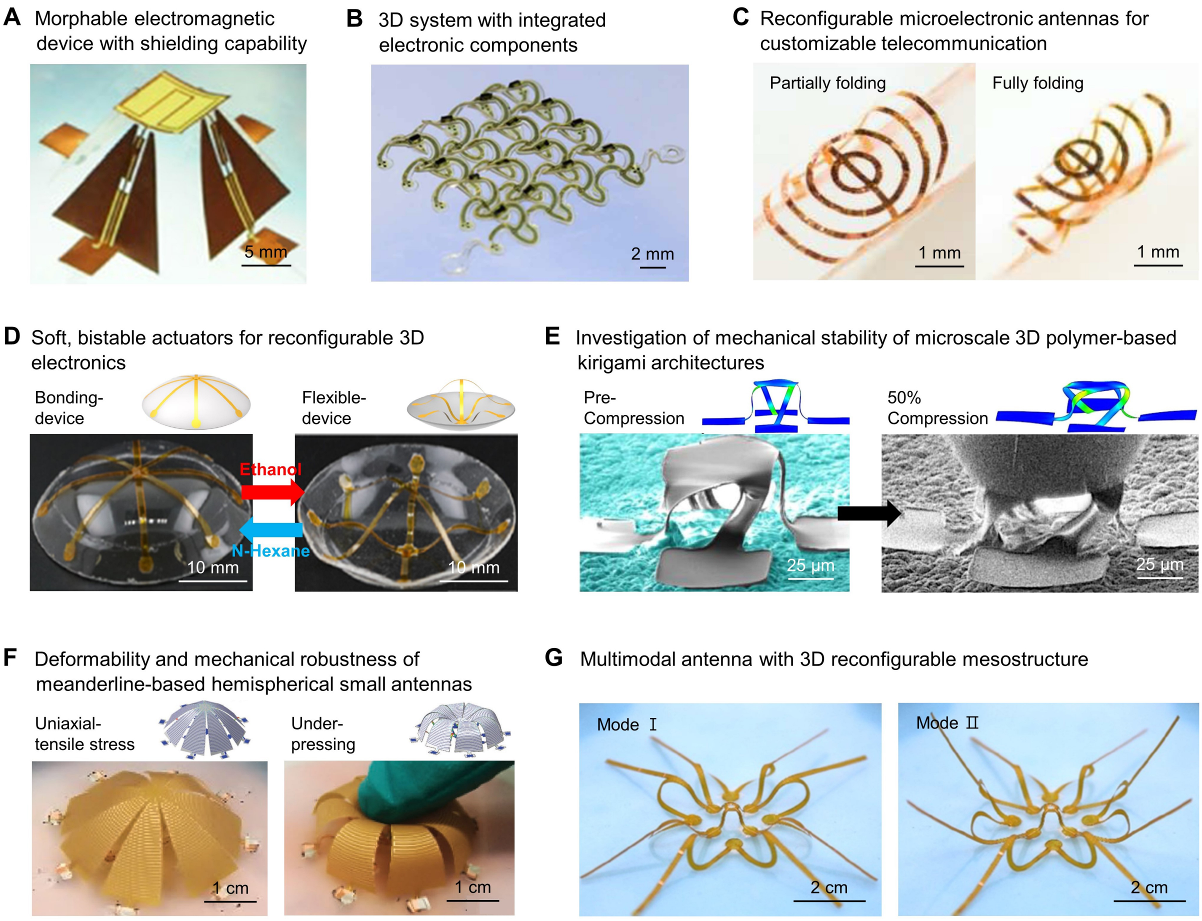

Figure 3. (A) 3D morphable mesostructures as switchable radio frequency electronic components with shielding capability. (Reproduced with permission from Ref.[143]. Copyright© 2018. Springer Nature); (B) image of 4-by-4 interconnected helical 3D arrays with integrated micro LEDs, heaters, thermistors, and electrodes. (Reproduced with permission from Ref.[51]. Copyright© 2021. American Association for the Advancement of Science); (C) partially and fully folded 3D mesoscale saddle structures formed from a 2D copper precursor of concentric circles. (Reproduced with permission from Ref.[144]. Copyright© 2022. American Association for the Advancement of Science); (D) different bonding modes of 3D bilayer PI sheets consisting of two cross PI ribbons. (Reproduced with permission from Ref.[145]. Copyright© 2021. American Chemical Society); (E) images of 3D buckled structure in the shape of a table with different compressive strains. (Reproduced with permission from Ref.[146]. Copyright© 2019. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim); (F) mechanically stable and electrically tunable hemispherical small antennas. (Reproduced with permission from Ref.[147]. Copyright© 2019. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim); (G) a multimodal antenna consisting of four pairs of reconfigurable components. (Reproduced with permission from Ref.[55]. Copyright© 2020. American Association for the Advancement of Science)

microvascular networks. Zhang *et al.* reported an origami-based microfolding strategy that enables the formation of 3D morphable microelectronic systems using a wide range of material classes, including single crystalline silicon, metallic nanomembranes, and polymers [Figure 3C][144]. Based on computational modeling, they predesigned a folding host and constructed a folding pathway to fabricate a freestanding 3D mesostructure with modulatory functionality and a complex configuration. This demonstrated the development of miniaturized electronic devices for customizable telecommunication, which have significant applicability in scenarios of limited design space and deformable carriers by fabricating mesoscale 3D antennas with various folded states. Chen *et al.* reported that a 3D electronic device can be reconstructed using the solvent-driven bistable structure of a silicon-oil extracted poly(dimethylsiloxane) (PDMS) sheet, which acts as a substrate [Figure 3D][145]. The PDMS substrate exhibited snap-through and snap-back behaviors by solvent stimulation, resulting in various bonding modes of the kirigami polyimide (PI) sheet adhered to PDMS. A frequency-reconfigurable small monopole antenna driven by a bistable substrate was presented as an application. Humood *et al.* fabricated polymer-based kirigami microscale structures and investigated the mechanical stability of various 3D architectures by confirming the resilient behavior for cyclically applied compression under different forces [Figure 3E][146]. The mechanical response of the 3D structures was confirmed to be stable and recoverable when compressed up to 50% of their initial height, and permanent changes in internal stress and curvature occur under extreme compression of 100%. With a deep understanding of the compressive behavior of kirigami-based soft MEMS devices, guidelines are presented to eliminate crack growth, which is critical for the fabrication of MEMS devices, including pressure and shear sensors. Liu *et al.* introduced a mechanically induced 3D assembly approach for the design and fabrication of high-quality meanderline-based hemispherical small antennas [Figure 3F][147]. External tensile strains were applied to reshape the elastomeric substrates and reversibly tune the wide range of center frequencies to adapt to changes in environmental conditions. The demonstration of a small antenna system whose frequency is tunable over a wide range and capable of maintaining high levels of mechanical strain suggests promising potential applications in many applications, including wireless wearables and bio-integrated electronics. Finally, Bai *et al.* fabricated a multimodal antenna capable of customizing distinct beamforming and discrete beam scanning [Figure 3G][55]. They demonstrated approximately 30 reconfigurable mesostructures with diverse geometric topologies by mechanically guiding the simplest ribbon geometries. Reconfigurable single antennas can replace array antennas to realize miniaturized and smart wireless devices and can be useful in cases with limited design space.

Light-emitting diode and photodetector

Optoelectronics aims to develop devices that enable the sourcing, detection, and control of light, and it shares its strategic importance by being interdependent with various fields such as electronics[148], information technology[149-152], and computer technology[153]. Accordingly, many efforts have been made to develop 2D flexible/stretchable optoelectronic devices with strict mechanical criteria to maintain electrical and optical properties despite mechanical deformation under various conditions[5,7,154]. In addition to these efforts, the construction of complex 3D optoelectronic systems has provided qualitatively improved performance, and it is possible to realize an efficient and highly functional optoelectronic device by designing an architecture similar to that of 3D systems commonly seen around, including biology or organism. Several methodologies have been proposed to implement 3D optoelectronic devices, and representative methods include buckling, which can expand the space between optoelectronic component pixels by stretching or shrinking elastomeric substrates[155], and the kirigami method, which can fold and convert 2D structures into 3D structures[156]. In this chapter, we introduce recent advances in the fabrication method and application of stretchable and flexible 3D optoelectronic devices [Figure 4].

Wang *et al.* fabricated a mechanically stable 3D wireless LED device using a shape memory polymer (SMP), a means to achieve a robust 3D framework [Figure 4A][157]. The recovery capability and programmability of the SMP provide novel routes to design freestanding 3D mesostructures and programmable microdevices. Furthermore, when the external force along the out-of-plane direction is applied to the LED device and removed using tweezers, the original shape is restored without noticeable damage, exhibiting essential mechanical robustness for various applications. Lee *et al.* demonstrated a mechanically assembled 3D photodetection and optical imaging system that enabled the measurements of the direction, intensity, and angular divergence properties of incident light [Figure 4B][158]. Based on the mechanics of ultra-thin graphene and MoS_2, MoS_2/graphene photodetector arrays were realized with origami-inspired complex 3D shapes such as an octagonal prism, an octagonal prismoid, and a hemisphere. The resulting system could track the direction and intensity of incident light through a 3D architecture, and the atomically thin MoS_2 and graphene could fabricate optically transparent devices to detect light passing through the device at two sensing positions. Lee *et al.* demonstrated an origami/kirigami-inspired LED array that can preserve the

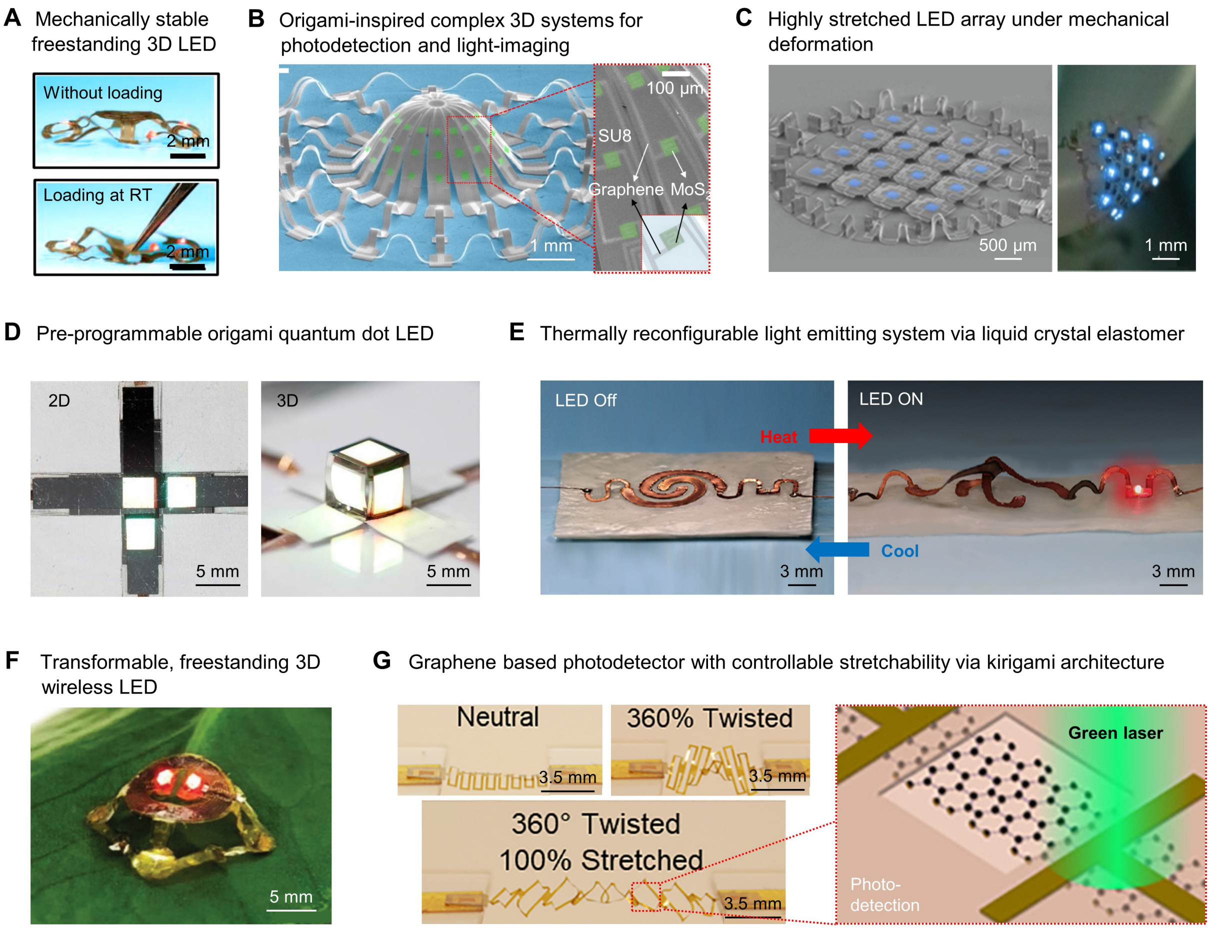

Figure 4. (A) Shape recovery behavior of 3D LED device before deformation and after load removal. (Reproduced with permission from Ref.[157]. Copyright© 2019. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim); (B) 3D hemispherical MoS2 photodetectors with interconnection. (Reproduced with permission from Ref.[158]. Copyright© 2018. Springer Nature); (C) operation of 3D display pixel arrays in a bent state by mechanical deformation. (Reproduced with permission from Ref.[155]. Copyright© 2022. Elsevier); (D) 3D architectures of QLED transformed from pre-programmed 2D planar device. (Reproduced with permission from Ref.[159]. Copyright© 2021. Springer Nature); (E) 2D and 3D configurations of light emitting system under cooling and heating of liquid crystal elastomer substrate. (Reproduced with permission from Ref.[160]. Copyright© 2021. American Chemical Society); (F) freestanding 3D LED with wireless power transmission capability on a leaf. (Reproduced with permission from Ref.[161]. Copyright© 2019. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim); (G) strain-insensitive graphene-based photodetection device under stretching and twisting. (Reproduced with permission from Ref.[156]. Copyright© 2020. Elsevier).

original image quality under stretching [Figure 4C][155]. The deformable LED pixel array can be stretched up to 100% without the deterioration of device performance by integration with a transparent epoxy frame. The 3D stretchable display is expected to improve the maximized space efficiency of electronic products whose sizes vary depending on their intended use. Kim *et al.* fabricated 3D foldable quantum dot LED (QLED) using laser patterning and metal etch-stop layers [Figure 4D][159]. The pre-programmed QLED paper transforms by controlled folding under external compressive forces. 3D electronic paper will not only be used for unconventional information displays and 3D decorative lighting but will also be a way to provide a new display form factor that can deliver realistic 3D information. Li *et al.* demonstrated a reconfigurable LED system utilizing the reversible shape-switching behavior of liquid crystal elastomer substrates [Figure 4E][160]. They induced a nematic-isotropic transition of liquid crystal molecules with remote thermal stimuli and mechanically controlled the on/off state of the LED. Tunable LED devices via remote thermal stimulation can provide important insights into the design of programmable 3D structures and systems, including origami/kirigami and deployable devices. Park *et al.* fabricated a wirelessly powered lighting system with a built-in capacitor [Figure 4F][161]. A freestanding LED was developed using transient materials capable of triggering 3D transformation and mechanical interlocking elements composed of female-type lugs and male-type hooks. Mechanical interlocking systems provide straightforward access to transformable or freestanding optoelectronics without material limitations. Yong *et al.* reported an atomically thin graphene-based deformable and strain-insensitive photodetection device with controllable stretchability via a kirigami-inspired architecture [Figure 4G][156]. The kirigami architecture enabled strategic redistribution of stress concentrations through kirigami notches and island bridge motifs. Through this strategy, a photodetection device that can be driven under high tensile and torsional deformation was demonstrated.

Energy devices

As microsystems become wireless and perform power-consuming tasks, the importance of microenergy devices capable of energy generation and storage in micro-autonomous systems is increasing. Although many energy-harvesting platforms such as solar cells[13,162,163], batteries[164-166], photovoltaic cells[167,168] and triboelectric devices[169,170] have made impressive progress in performance, further improvements in shape deformability and mechanical/electrochemical stability against deformation are required for a wide application. In this regard, the implementation of an energy device with a complex and hierarchical 3D geometry can achieve excellent mechanical properties and stable operations even under extreme deformation. It can also increase the areal capacity, surface area accessibility, and charge/discharge speed rate[171]. Considerable efforts have been made to achieve these improvements, and various manufacturing concepts of energy harvesters applicable to 3D structures with various forms are introduced in this chapter [Figure 5].

Han *et al.* demonstrated 3D piezoelectric mesostructures by a controlled, nonlinear buckling process, converting thin films of piezoelectric polymers into sophisticated 3D piezoelectric microsystems [Figure 5A][172]. These ultralow-stiffness 3D mesostructures, composed of functional piezoelectric materials, created interesting opportunities for energy harvesting from complex modes of motion induced by vibrations. Kim *et al.* developed a highly stretchable piezoelectric energy harvester by grafting a kirigami structure on a flexible polyvinylidene fluoride (PVDF) film [Figure 5B][173]. To overcome the low piezoelectric coefficient of PVDF, the generation of opposite charges was eliminated using phase depolarization, and the neutral axis was optimized using a backing layer. Furthermore, the kirigami pattern has been designed to generate the highest average stress within the constraint by performing finite element analysis, resulting in high performance. Yang *et al.* also fabricated a high-areal MXene aerogel capacitor with microlattices assisted by templates developed using 3D printing techniques [Figure 5C][174]. Transition metal carbides (MXene), a promising material for high-performance energy storage, were injected into a 3D-printed hollow template to produce an MXene aerogel with effective electrolyte penetration and rapid ion diffusion. The high design freedom of structures and diversity of material choices could be obtained using various 3D printing-based direct fabrication methods. Xia *et al.* introduced a new mechanism for dynamically reconfiguring materials by exploiting electrochemically driven alloying/dealloying reactions [Figure 5D][175]. 3D silicon-coated microlattices were transformed into sinusoidal patterns via cooperative buckling in response to an electrochemical silicon-lithium alloying reaction. Various architecture designs could be achieved by programming the domain boundaries to form particular patterns and exhibit the capabilities of implantable energy storage systems. Guo *et al.* demonstrated a kirigami-based stretchable, deformable, inorganic thermoelectric generator (TEG) for body heat energy harvesting [Figure 5E][176]. The 3D adjustable architecture enables vertical heat conduction to utilize the temperature difference between the nonplanar heat source and the environment. The kirigami-based TEG exhibited high-generation performance with deformation reliability during body movement. Miao *et al.* fabricated magnetic material-based energy-harvesting systems, including 3D piezoelectric devices, for noncontact conversion of

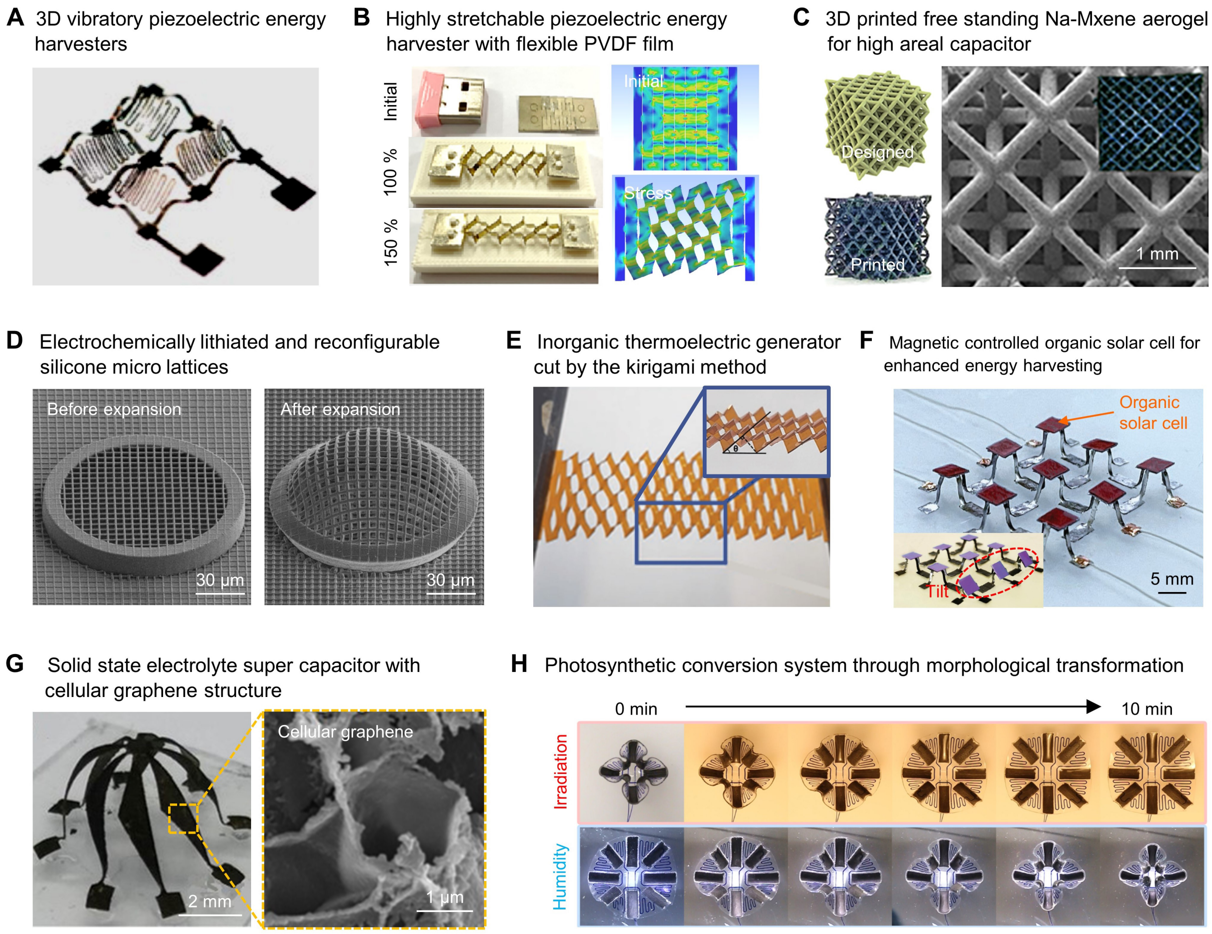

Figure 5. (A) 3D serpentine array for energy harvesting from multidirectional vibrations. (Reproduced with permission from Ref.[172]. Copyright© 2019. Springer Nature); (B) stretching behavior of kirigami-cut PVDF film and finite element analysis for application design. (Reproduced with permission from Ref.[173]. Copyright© 2022. Springer Nature); (C) 3D printed MXene aerogel with hollow octet truss architecture for capacitors. (Reproduced with permission from Ref.[174]. Copyright© 2022. American Chemical Society); (D) reconfiguration of electrochemically driven micro-architecture out-of-plane buckling. (Reproduced with permission from Ref.[175]. Copyright© 2019. Springer Nature); (E) stretchable 3D thin-film TEG by kirigami cuts. (Reproduced with permission from Ref.[176]. Copyright© 2022. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim); (F) organic solar cell-integrated 3D table array under magnetic controlled state. (Reproduced with permission from Ref.[177]. Copyright© 2021. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim); (G) kirigami-inspired windmill-like structures with laser-induced cellular graphene for solid-state electrolyte supercapacitor. (Reproduced with permission from Ref.[178]. Copyright© 2018. American Chemical Society); (H) unfolding and folding of photo-microreactor under light irradiation and humidified environment. (Reproduced with permission from Ref.[179]. Copyright© 2022. American Association for the Advancement of Science).

mechanical energy and 3D solar tracking systems [Figure 5F][177]. The temporary magnetization of materials exhibited various locomotion such as local deformation and unidirectional tilting under the precise control of the magnetic field, improving energy-harvesting efficiency. Ling *et al.* demonstrated programmed 3D hierarchical architectures of cellular graphene, which typically exhibits relatively low stretchability due to its porous microstructure, via mechanically well-guided 3D assembly [Figure 5G][178]. A 3D solid-state electrolyte supercapacitor with cellular graphene exhibited stable electromechanical properties under cyclic deformation. Pan *et al.* fabricated a photosynthetic conversion device that can respond to temperature, humidity, and light irradiance by embedding stimulus-responsive materials [Figure 5H][179]. Responsive movements induced the preset origami transformation, and the photo-microreactor fed the environmental stimuli back positively to photosynthetic conversion through morphological transformation.

Bio-medical devices

Accurate monitoring of the physiological properties of 3D biological systems can improve our understanding of the evolution and origin of abnormal behaviors or disease states[180,181], as well as the interactions associated with the development of neural systems[182-184]. Furthermore, an in-depth analysis of soft living tissues can serve as the basis for diagnosing and treating diseases[185-187]. Thus, the integration of traditional medical technology and biological systems can establish pathways to improve health and prolong life[188-190]. However, biological systems, including plants (e.g., stems and seeds) and animals (e.g., hearts, brains, and blood vessels), have mostly complex 3D curved surfaces, some with dynamic and time-varying features. Nevertheless, many biomedical technologies have rigid, planar, and 2D shapes, which limit their functional interfaces to localized areas of 3D structures, near the bottom contact surface. In this regard, the development of fabrication approaches to allow conformal contact of biomedical systems with 3D biological surfaces is important for highly reliable information interactions between them. In addition, as physical coupling, it is necessary to enable complex optical/electrical/chemical exchange between abiotic and biological systems. In this chapter, we introduce several studies that have developed 3D biomedical systems and demonstrated various applications such as health monitoring, human-machine interfaces, therapeutic devices, artificial tissues/organs, and basic biomedical research [Figure 6].

Yang *et al.* demonstrated the stable attachment of millimeter-scale flexible electronic/optoelectronic systems, such as wireless cardiac pacemakers and multielectrode epicardial arrays, to vital internal organs with bioelectronics-tissue interface materials (BTIMs) [Figure 6A][105]. BTIMs are mechanically compliant, conductive, and optically transparent and have chemically controlled bioabsorption rates, allowing them to bond strongly to both device and internal organ surfaces with long-term stability. Skylar-Scott *et al.* reported a biological manufacturing method of assembling organ-building blocks into living matrices with a high cellular density [Figure 6B][191]. Perfusable vascular channels in living matrices were introduced through 3D bioprinting. They could fabricate the arterial vascular network geometry within a cardiac tissue matrix using a patient-specific, cardiac structural model. Xue *et al.* assembled a tiny 3D rhomboid ribbon microscale structure with a lateral feature size of a sulcus [Figure 6C][192]. Although the complex sulcus topology exhibited obvious bending/torsional deformation during assemblies of 3D electronic systems, a quantitative mechanical modeling strategy was used to transform curved elastomer substrates into planar or cylindrical configurations. Gu *et al.* introduced a scalable platform employing a 3D high-performance field effect transistor (FET) array obtained through buckling at predesigned hinge locations of a 2D precursor [Figure 6D][193]. The 3D FET array enables accurate recording of transmembrane potentials in electrogenic cells with minimally invasive cellular interfacing and revealing signal conduction paths in cardiac muscle tissue constructs via intracellular recordings. Chen *et al.* fabricated 3D biomimetic cell-laden microstructures that could mimic the 3D hierarchical structure of the native tissue using engineered tissue models and the compressive buckling method [Figure 6E][194]. By incorporating 2D microfabrication methods into 3D cellular engineering, the proposed method shows the possibility of solving problems such as low spatial resolution, cell viability, and the limited choice of bioink due to conventional 3D bioprinting. Yan *et al.* fabricated a biomimetic, artificial soft 3D network system using helical microstructures as building blocks, which connect lattice nodes [Figure 6F][195]. The developed system exhibited defect-insensitive and J-shaped stress-strain responses, which are closely matched with those of real biological tissues. These findings are expected to provide many opportunities for flexible bio-integrated applications. Park *et al.* introduced microfabricated 3D frameworks as multifunctional neural interfaces that simultaneously include electrical, optical, chemical, and thermal interfaces to cortical spheroids, organoids, and assembloids [Figure 6G][196]. The 3D complex architecture could exploit reversible engineering control over shapes, sizes, and geometries to match organoids/spheroids of interest. It is expected that this platform will improve our understanding of basic neuroscience such as the formation and regrowth of bridging tissues across a pair of spheroids. Huang *et al.* developed miniaturized wafer-integrated multielectrode array

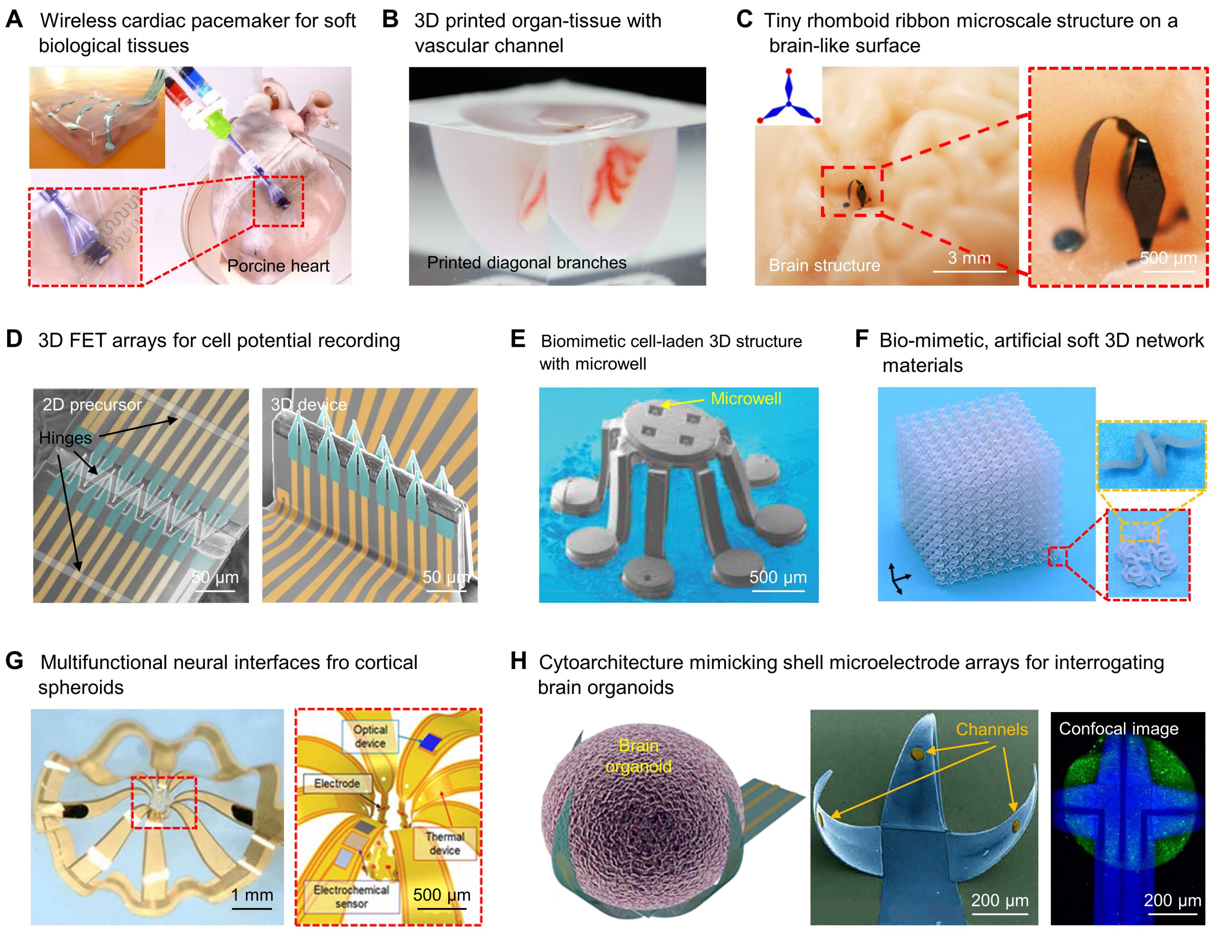

Figure 6. (A) Adhesion between bioelectronic devices and biological tissues with photocurable bioelectronics-tissue interface materials. (Reproduced with permission from Ref.[105]. Copyright© 2021. Springer Nature); (B) 3D printed arterial vascular network geometry within a cardiac organ-building block matrix. (Reproduced with permission from Ref.[191]. Copyright© 2019. American Association for the Advancement of Science); (C) ordered assembly of 3D rhomboid microscale structure on the complex non-developable surface. (Reproduced with permission from Ref.[192]. Copyright© 2022. American Association for the Advancement of Science); (D) 2D to 3D transformation of 10 FET arrays capable of interfacing cardiomyocytes. (Reproduced with permission from Ref.[193]. Copyright© 2022. Springer Nature); (E) octopus-shaped cell-laden 3D structures with high aspect ratio legs. (Reproduced with permission from Ref.[194]. Copyright© 2021. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim); (F) 3D printed biomimetic soft 3D network materials with helical filamentary microstructure and cubic lattice topology. (Reproduced with permission from Ref.[195]. Copyright© 2020. Springer Nature); (G) 3D multifunctional mesoscale framework as an interface to a neural spheroid. (Reproduced with permission from Ref.[196]. Copyright© 2021. American Association for the Advancement of Science); (H) 3D shell microelectrode arrays for potential recording from encapsulated brain organoids. (Reproduced with permission from Ref.[197]. Copyright© 2021. American Association for the Advancement of Science).

caps with optically transparent polymer-coated metals that enable the recording and stimulation of activity from electrogenic cells [Figure 6H][197]. By mechanical simulation, the folding of the minicamp becomes tunable, resulting in various recordings from organoids of different sizes.

Sensors

A sensor is an element that detects various physical/chemical information around it and extracts or processes new information to provide a specific service. It is embedded in various devices depending on the purpose. Accordingly, sensors that can be applied to various types of objects are being actively developed, and many advantages can be obtained by introducing a 3D architecture to the sensor. Sensors that can be applied to non-flat surfaces such as curved surfaces and spheres have been developed through 3D geometric design, and high-performance sensors that exceed human senses such as sight, hearing, and touch can also be realized[198,199]. In addition, a multifunctional sensor capable of simultaneously recording pressure, shear force, and bending, along with sensing targets such as temperature, current, and humidity, based on the deformability of 3D structures, has been proposed[200,201]. Recently, sensing devices with bioinspired sensing capabilities, such as temperature and deep-versus-fine touch contact sensing, have been reported by combining actuators to form complex sensor network systems through 3D printing[202,203]. Along with these developments of functionalities, the 3D arrangement of sensors enables spatiotemporal mapping of responses, improves the integrated density, and can also provide 3D vector field detection. In this chapter, we introduce a high-performance sensor based on 3D structures that can detect various external stimuli [Figure 7].

Kim *et al.* fabricated macro-, meso- and microscale 3D fliers inspired by wind-dispersed seeds using the mechanically guided assembly of 3D mesostructures [Figure 7A][201]. The 3D fliers were designed to be integrated with active electronics and colorimetric sensors to fly without power and gather information across natural environments or city settings. They exhibited significant potential for various applications, including atmospheric monitoring, complementing the conventional gravimetric and optical particle-counting methods. Peng *et al.* fabricated a porous flexible strain sensor that can monitor human motion by casting polyurethane/carbon nanotube composites into a 3D printed sacrificial mold [Figure 7B][204]. The strain sensor exhibited high stretchability and excellent recoverability. The potential of user-specific stretchable wearable sensors was demonstrated using the advantage of 3D printing of unlimited geometry designs. Won *et al.* demonstrated a 3D microelectromechanical sensor that can simultaneously measure temperature, normal force, shear force, and bending using monocrystalline silicon nanomembranes as piezoelectric elements [Figure 7C][205]. A table-like 3D structure was implemented through mechanically induced geometric transformation (buckling), and scalable production of interconnected array devices with a spatiotemporal mapping function was demonstrated. Becker *et al.* reported a high-density integrated active matrix magnetic sensor with a 3D magnetic vector field-sensing capability that enables remote recognition of moving objects [Figure 7D][206]. A 3D magnetic sensor array was fabricated through a micro-origami process of a self-folding polymer platform with embedded sensors. The applicability to real-time multidirectional tactile perception was demonstrated through the integration with an electronic skin embedded with magnetic hair. Liu *et al.* proposed a self-healing kirigami assembly strategy that allows planar sheets to completely wrap a 3D curved surface for conformal electronics [Figure 7E][207]. The function of the device is guaranteed by maintaining electrical conductivity using a conductive self-healing material. By applying the proposed technique to a spherical surface, a multifunctional wind-sensing system was fabricated to detect the pressure caused by wind blowing from various angles. Katiyar *et al.* mimicked the biological eyes by combining the mechanical superiority of ultra-thin silicon and deformable optoelectronics with hemispherical geometry via pneumatic pressure-induced expansion [Figure 7F][208]. In addition, the strain derived from pneumatic pressure causes shrinkage in the bandgap of Si, providing photo-sensing capability beyond its fundamental absorption limit in Si nanomembrane photodetectors. Cheng *et al.* fabricated a 3D ribbon-shaped flexible resistance-type vibration sensor that can measure low-frequency vibration with long-term stability [Figure 7G][209]. They demonstrated that the fatigue life of 3D ribbon-like flexible electronics can be significantly extended by adopting an anti-fatigue strategy that converts metal-dominated failures into desired polymer-dominated failures. This anti-fatigue design shows the possibility of long-term health monitoring or human-like robotic acceptance. Wang *et al.* fabricated complicated 3D interconnected networks of horseshoe-shaped active components, as demonstrated with a stretchable capacitive pressure sensor array [Figure 7H][210]. Using 3D printing techniques, they constructed complex structures with a high spatial resolution that can induce the photopolymerization of the local area triggered by UV projection. According to the finite element analyses, the precisely controlled 3D microstructures exhibited exceptional stretchability,

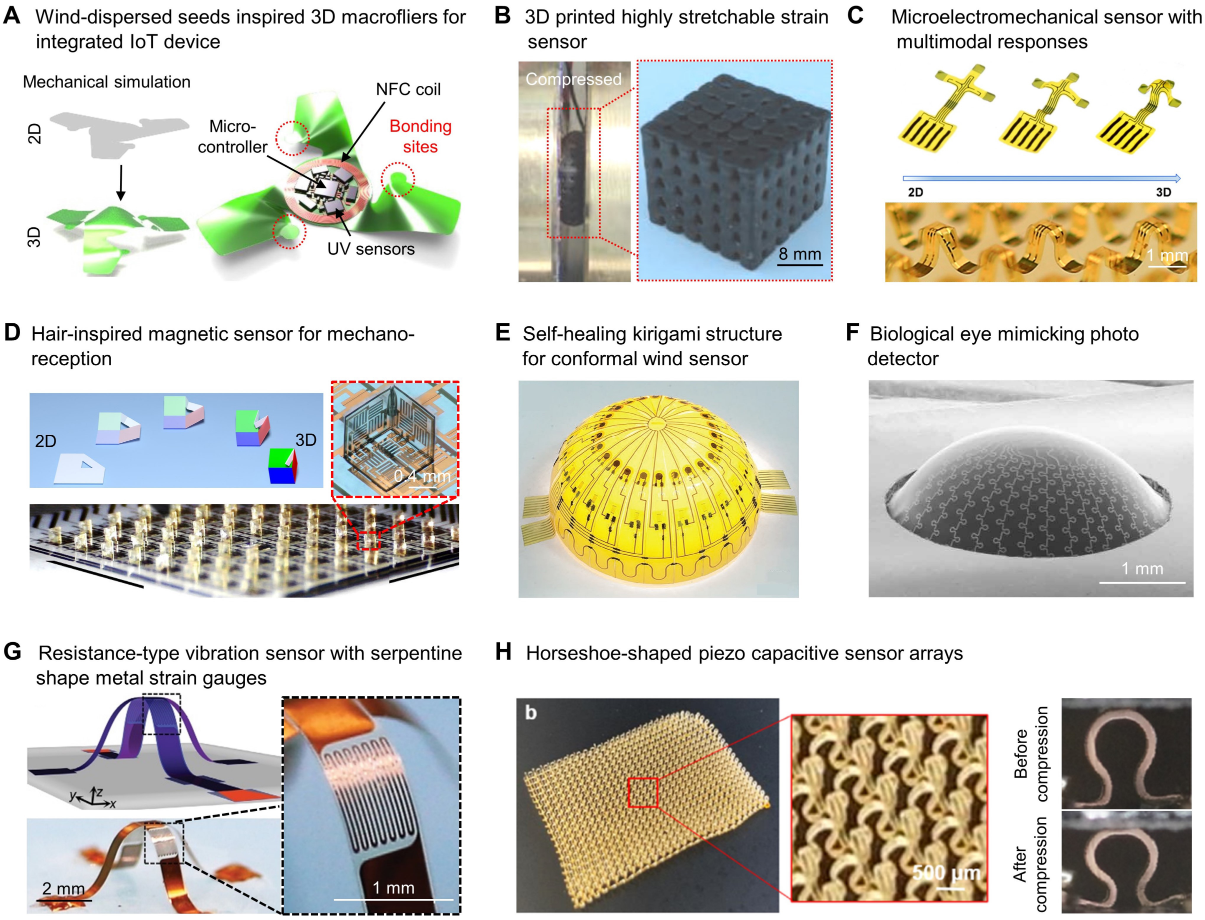

Figure 7. (A) 3D wireless macroflier for measuring fine dust pollution through light dosimetry. (Reproduced with permission from Ref.[201]. Copyright© 2021. Springer Nature); (B) indirect 3D printed strain sensor with porous lattice architecture for motion monitoring. (Reproduced with permission from Ref.[204]. Copyright© 2021. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim); (C) electromechanical sensor array for measuring the spatial distribution of external loads. (Reproduced with permission from Ref.[205]. Copyright© 2019. American Chemical Society); (D) micro-origami magnetic sensor array composed of self-folded polymer cube. (Reproduced with permission from Ref.[206]. Copyright© 2022. Springer Nature); (E) hemispherical device with 24 flexible pressure sensors for wind-sensing systems. (Reproduced with permission from Ref.[207]. Copyright© 2022. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim); (F) convex hemispherical-shaped device with stretchable photodetector array. (Reproduced with permission from Ref.[208]. Copyright© 2020. American Association for the Advancement of Science); (G) 3D mechanically reliable vibration sensor capable of withstanding prolonged fatigue life. (Reproduced with permission from Ref.[209]. Copyright© 2021. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim); (H) 3D printed network of the horseshoe-shaped microstructure array for pressure sensing. (Reproduced with permission from Ref.[210]. Copyright© 2021. American Chemical Society).

conformability, strain-insensitive electrical properties, and cyclic stability.

Actuators

Actuators, which can perform specific tasks by mimicking behaviors or methods that organisms use to adapt to the environment, are attracting considerable attention for their applicability in many fields, from tools for surgery[211] to transport machines for moving objects[212]. The introduction of precisely controlled 3D structure formation methods, including mechanical buckling, origami, kirigami, and 3D printing methods, into actuator manufacturing enables the implementation of actuators with complex 3D layouts beyond simple structures such as spheres, tubes, rods, and arcs. It has also been reported that these 3D actuators can achieve unique movement and behaviors, including bending, crawling, walking, and rotation, without space constraints[213,214], and the integration with soft materials can improve the performance required for practical applications such as strain, speed, energy efficiency, and repeatability[215,216]. In this chapter, we introduce actuators with 3D architectures that can perform very delicate and complex tasks in several fields, including electronics and robotics [Figure 8].

Ning *et al.* reported a micro-sized complex 3D mechanical framework that integrated multiple, independently addressable piezoelectric thin-film actuators for vibration excitation and precise control through the guided assembly of heterogeneous materials [Figure 8A][217]. This approach combines transfer printing for integrating heterogeneous materials and structural buckling for 2D to 3D geometric transformation to realize complex and hierarchical architectures. In addition, the location of the piezoelectric material and metal layer was optimized to ensure integrity during compression buckling based on quantitative finite element analysis. This study demonstrated the possibility of measuring fluid properties with separated sensitivity to viscosity and density based on multiple 3D vibration modes of piezoelectric microactuators. Xiang *et al.* reported photo-driven hydrogel actuators that can be used in underwater photo-mechanical applications [Figure 8B][218]. Hydrogels are made of transparent polyurethane, consisting of dynamically covalent crosslinked hexaarylbiimidazole and permanently crosslinked pentaerythritol, and exhibit anisotropic deformation in response to visible light with mechanical stability and repeated utility. As one of the applications of biomimetic actuators, underwater flowers with rapid photo-driven locomotion have been demonstrated. Han *et al.* reported submillimeter-scale terrestrial robots with complex 3D geometries and multi-material construction, capable of unusual actuation modes on a solid surface [Figure 8C][219]. The balance between the force associated with the shape memory alloy under heating conditions and the elastic resilience of the encapsulating shell provided the basis for reversible deformation. It has been shown that various modes of locomotion are possible, from bending, twisting, and expansion at global heating to linear/curve crawling, walking, turning, and jumping at laser-induced local heating. By integrating a photonic component and a colorimetric sensor into the proposed actuator body, the possibility of wireless communication and localization was suggested. Deng *et al.* reported a laser-rewritable magnetic composite film that could be reprogrammed digitally using a direct laser writing method [Figure 8D][220]. The magnetic anisotropy of the composite film was encoded through digital laser writing into the local area, resulting in multimodal 3D shaping under the same actuation magnetic field. They fabricated a multistate electrical switch as an application example of a multistate 3D structure driven by magnetically induced buckling. Skylar-Scott *et al.* introduced a method for designing and fabricating voxelized soft matter using multi-material multi-nozzle 3D printing, where the composition, function, and structure of materials can be spatially programmed [Figure 8E][212]. Using this method, they fabricated a pneumatic actuator-embedded soft robot with millipede-like features utilizing a combination of rigid and soft elastomers. By arranging the two actuator sets asymmetrically, the power stroke for each actuator group can achieve forward movement. Zhu *et al.* created electrothermal actuator arrays capable of rapid, large-angle, and reversible elastic folding through the controlled and localized Joule heating of micro-origami creases [Figure 8F][221]. The proposed system is capable of reprogramming the folds of these creases by overheating, providing a method for fabricating a permanent and plastically folded 3D shape. A 3D functional microsystem that flexibly folds and unfolds flap wings according to the current was demonstrated. Yi *et al.* proposed a manufacturing strategy that can rapidly fabricate magneto-active machines on a large scale by integrating the roll-to-roll processing of 2D patterns and 3D origami folding using magnetic composite sheets, where hard magnetic particles are dispersed in a polymer matrix [Figure 8G][222]. The introduction of a roll-to-roll platform enables the automatic production of 2D patterns of various geometries with high throughput. The magnetic sheet has magnetic responsiveness while maintaining paper-like foldability so that 3D magneto-origami machines with various shapes and movements could be manufactured on demand.

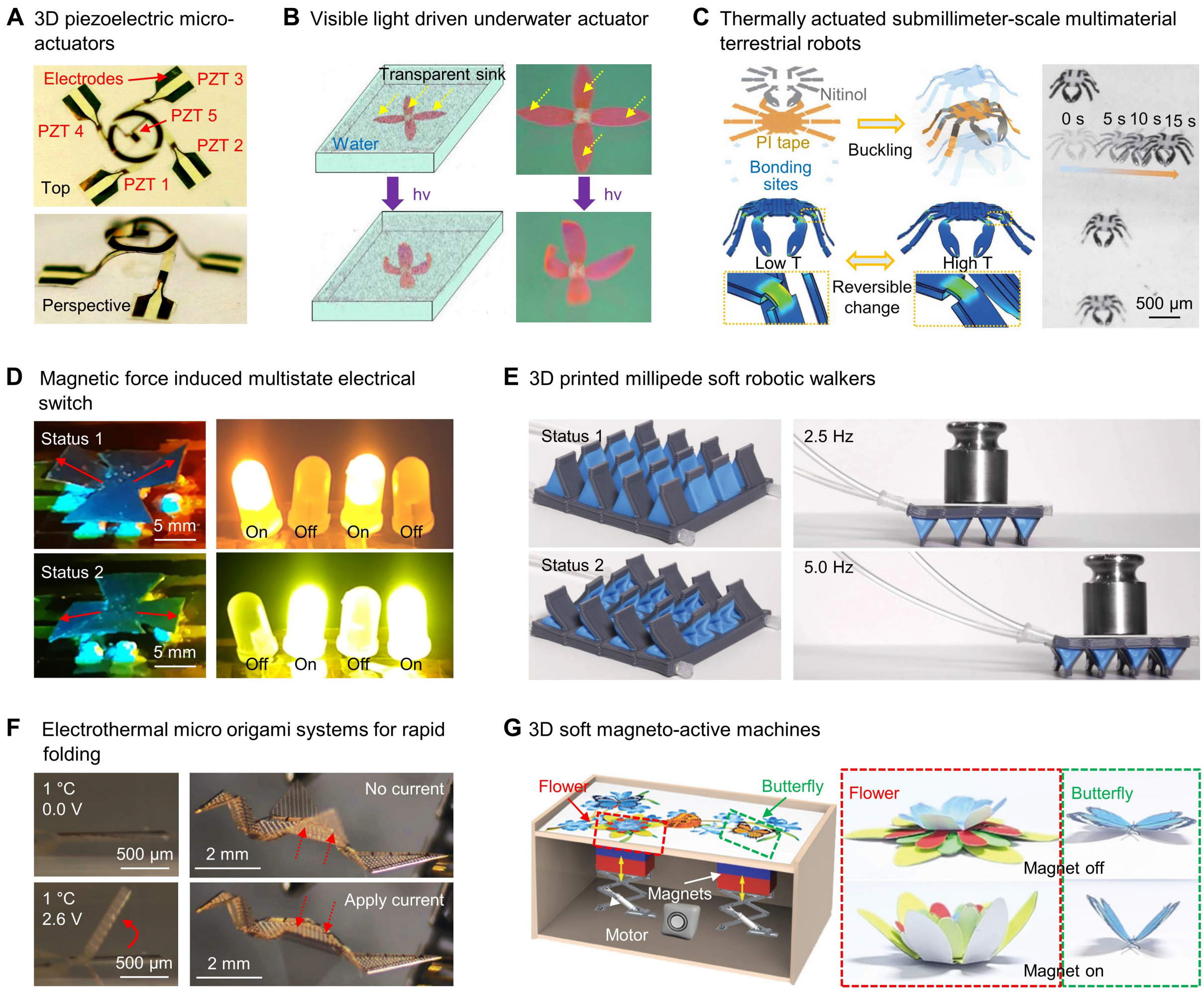

Figure 8. (A) 3D mechanical framework with five independently addressable piezoelectric microactuators. (Reproduced with permission from Ref.[217]. Copyright© 2018. American Association for the Advancement of Science); (B) photo-driven biomimetic flower capable of underwater movement. (Reproduced with permission from Ref.[218]. Copyright© 2021. Elsevier); (C) directional locomotion of submillimeter-scale 3D peekytoe crab. (Reproduced with permission from Ref.[219]. Copyright© 2022. American Association for the Advancement of Science); (D) a multistate electrical circuit made of magnetic responsive soft material switch. (Reproduced with permission from Ref.[220]. Copyright© 2020. Springer Nature); (E) 3D printed soft robotic walkers composed of 16 interconnected pneumatic actuators. (Reproduced with permission from Ref.[212]. Copyright© 2019. Springer Nature); (F) micro-origami system capable of wing flapping under current stimulation. (Reproduced with permission from Ref.[221]. Copyright© 2020. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim); (G) magnetic responsive 3D origami machines with various shapes and movements. (Reproduced with permission from Ref.[222]. Copyright© 2022. Springer Nature)

Mechanical/optical meta-materials

Metamaterials are made by periodically arranging metals or dielectric materials that are significantly smaller than the wavelengths of light of electromagnetic waves, or by designing them to have a very sophisticated geometry. Generally, metamaterials exhibit artificial properties that do not exist in nature through methods, where a sub-wavelength metal/dielectric structure resonates with the electric and magnetic fields of incident waves, or by sophisticated design to have excellent mechanical properties. To improve the performance of metamaterials with unique properties, abundant spatial controllability is required, and 3D configurations provide an opportunity to compensate for this deficiency. For example, 2D metamaterials typically have limited controllability of their properties along the z-axis direction, whereas metamaterials composed of 3D architectures not only have controllability over the z-axis[223,224] but also exhibit more functionality and strong non-reciprocal behaviors[225]. In addition, through mechanical deformation or reconfiguration of the 3D assembly constituting these metamaterials, their characteristics can be dramatically improved or tuned according to the purpose. With the development of 3D metamaterials, various devices in imagination can be realized, and metamaterials have high potential applications in various fields. Thus, in this chapter, we review studies on fabricated 3D metamaterials through periodic arrangements of mesostructures or elaborate designs [Figure 9].

Cheng *et al.* demonstrated a dome-shaped hierarchical metamaterial with a gradient helical structure and ultrahigh strength and plasticity, inspired by the Pantheon in Rome, which can withstand high loads with low density [Figure 9A][226]. The introduction of the helical arch structure induced a property transition from brittle to ductile and could have high compliance and energy absorption capacity. They demonstrated that their proposed strategy is a promising method to mitigate the instability of ductile materials with the torsional effect of spiral arch domes and to suppress the decay of brittle composite materials through energy dispersion. Pan *et al.* fabricated a bifunctional chiral metasurface with giant asymmetric chirality in the mid-infrared range by bending a 3D bent surface through origami fabrication using a focused ion beam (FIB) [Figure 9B][227]. The tensile stress generated from the FIB induced an asymmetrically curved array of split ring resonators, resulting in the formation of a metasurface with abundant spatial degrees of freedom. The giant circular dichroism and asymmetric chirality properties are expected to promote the design of multifunctional chiral optical devices. Fan *et al.* presented a 3D flexible frequency-selective surface (FSS) that can be conformally attached to complex surfaces while maintaining stable transmission performance [Figure 9C][57]. Through mechanical buckling, the 3D metal structure is precisely controlled to induce the elasticity of the FSS, increasing inductance inside the metal cell and decreasing capacitance between unit cells. The proposed technology proved to be an efficient method for applying technologies such as electromagnetic wave shielding and spatial filtering to non-developable and flexible surfaces. Farzaneh *et al.* fabricated mechanical metamaterials with user-specified alternating Poisson's ratios, sequentially deformed by leverage principles of differential stiffness and self-contact [Figure 9D][228]. The degree of freedom in the unit cell design was guaranteed through an analytical approach using complementary software tools capable of designing 2D and 3D metamaterials. Finally, it is demonstrated that an alternating Poisson's ratio can be achieved even when a 3D lattice consisting of microscale unit cells is extended to a desired 3D volume. Chen *et al.* demonstrated an on-chip and electromechanically reconfigurable nano-kirigami system with optical functionality driven by the electrostatic force between a top-suspended gold nanostructure and a bottom silicon substrate [Figure 9E][56]. Through the design of the nano-kirigami pattern, they could achieve broadband non-resonant optical reconstruction at visible wavelengths and narrowband resonant optical reconstruction at near-infrared wavelengths. The proposed optical nano-kirigami design can be reconstructed with high contrast at the submicron level, proving its applicability to fields such as physics, nanophotonics, photonics, and MEMS.

Micro-fluidic system

Microfluidic engineering is a technology that can handle a small amount of fluid using microchannels (typically tens to hundreds of microns) and has been applied to various fields, including lap-on chips, drug delivery systems, and biopharmaceuticals[229-231]. For further advances in microfluidic technology, extending microfluidic networks from 2D to 3D is considered a promising method for improving fluid manipulation performance such as high-efficiency mixing, separation, and detection. Moreover, complex microfluidic structures in 3D can achieve complexity that is difficult to obtain on the 2D plane; therefore, they are expected to be actively used in biological vascular network simulations, especially for disease model investigation, tissue development, and drug screening[232,233]. Thus far, many methodologies, including mechanical buckling and 3D printing, have been developed to fabricate 3D microfluidics, and this chapter introduces various applications of 3D microfluidic channels with complex structures [Figure 10].

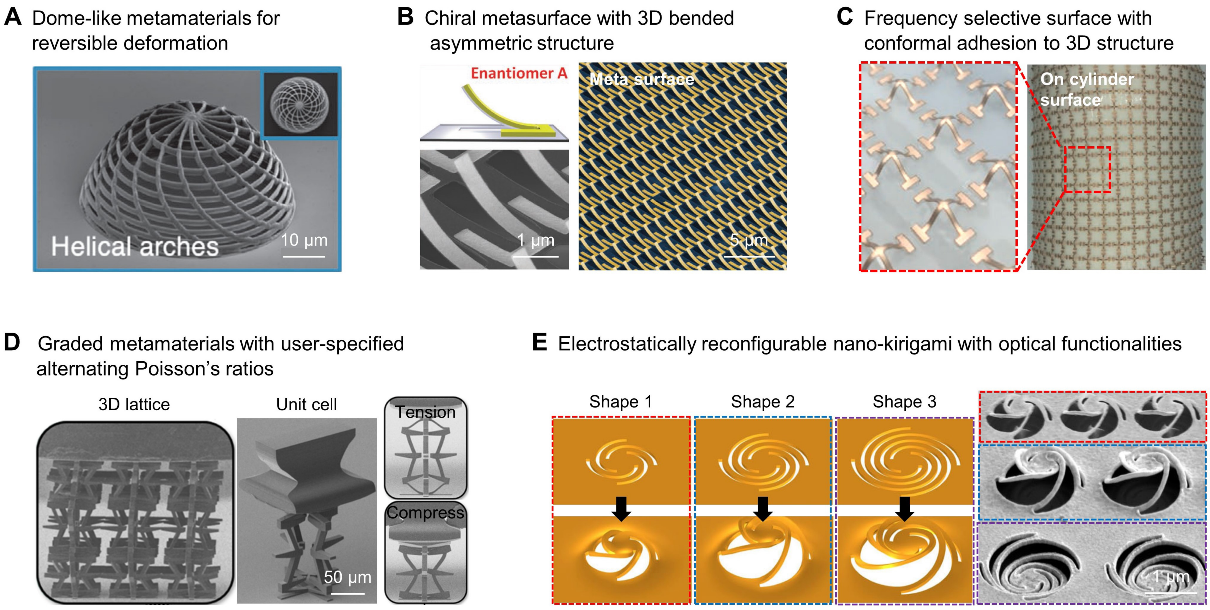

Figure 9. (A) Microdomes with helical arch architecture for ultrahigh strength and plasticity. (Reproduced with permission from Ref.[226].Copyright© 2021. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim); (B) large array of bent metasurface with chiral enantiomers. (Reproduced with permission from Ref.[227].Copyright© 2021. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim); (C) flexible 3D frequency-selective surface attached to a cylindrical surface. (Reproduced with permission from Ref.[57].Copyright© 2022. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim); (D) microlattice of the repeating unit cell with alternating Poisson's ratio. (Reproduced with permission from Ref.[228].Copyright© 2022. Springer Nature); (E) 3D spiral structures with different angled arcs for optical reconstruction. (Reproduced with permission from Ref.[56].Copyright© 2021. Springer Nature).

Weigel *et al.* reported the development of microfluidic devices with tunable mechanical properties by integrating accessible 3D printing technology and commercially easy-to-prepare starting materials [Figure 10A][234]. A microfluidic cell with optical transparency, flexibility, and a minimal feature size was fabricated by developing a highly stretchable polymer material for the high-resolution manufacturing of micromaterial systems. Microfluidic cells can compete with PDMS-based microfluidic devices in terms of applicability to the customization of fluid flow and emulsion formation. This technology presents an approach for fabricating functional 3D microfluidic devices that require high mechanical flexibility desired by users through predesigns. Bertassoni *et al.* reported a bioprinted agarose template fiber-based 3D micro-molding technique that can embed a functional and perfusable microchannel network with various architectures in photo-crosslinkable hydrogel constructs [Figure 10B][235]. They demonstrated the scalability of the method by applying it to various hydrogels, including methacrylated gelatin (GelMA), star poly(ethylene glycol-co-lactide) acrylate, poly(ethylene glycol) dimethacrylate, and poly(ethyleneglycol) diacrylate. In particular, cell viability, differentiation, and overall tissue functionality have been proven through microvascular channels made of gelatin (GelMA) hydrogels as a platform. Wu *et al.* introduced omnidirectional 3D printing techniques for fabricating 3D biomimetic microvascular networks embedded in hydrogel matrices by tailoring the chemical and rheological properties of fugitive ink as well as photopolymerizable hydrogel reservoir and fluid filler [Figure 10C][236]. By designing a liquid filler with the same chemical function, but with a lower viscosity than the photopolymerizable reservoir, it immediately fills local void spaces formed as the deposition nozzle passed through the reservoir, resulting in a mechanically robust and chemically crosslinked matrix. Through this methodology, it was possible to obtain a microvascular network with a hierarchical branching topology subdivided into numerous microchannels with a diameter of 200-600 μm between two large channels. Wang *et al.* reported 3D shape-programming microfluidic structures with various geometries, including open mesh structures, through compression

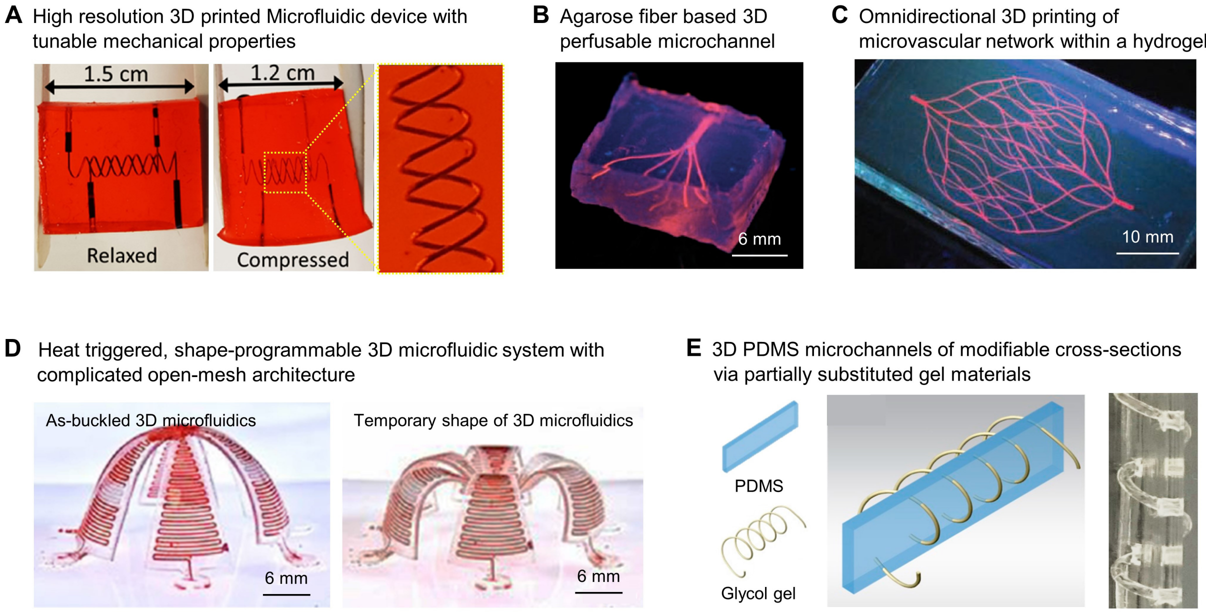

Figure 10. (A) Material flexibility of 3D printed microfluidic devices with minimal feature size. (Reproduced with permission from Ref.[234]. Copyright© 2021. American Chemical Society); (B) bioprinted templates enclosed in GelMA hydrogels and respective microchannels perfused with a fluorescent microbead suspension. (Reproduced with permission from Ref.[235]. Copyright© 2014. The Royal Society of Chemistry); (C) 3D microvascular via omnidirectional printing within a hydrogel matrix. (Reproduced with permission from Ref.[236]. Copyright© 2011. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim); (D) 3D microfluidics in "Umbrella" structure programmed from original shape to a deformed shape under external forces. (Reproduced with permission from Ref.[237]. Copyright© 2022. American Chemical Society); (E) schematic and optical image of the helical pattern of gel fiber template fixed on punctured PDMS. (Reproduced with permission from Ref.[238]. Copyright© 2019. Multidisciplinary Digital Publishing Institute).

buckling of a bilayer composed of PDMS and SMPs [Figure 10D][237]. The shape memory effect under thermal stimuli of SMP can return to its original shape after structural deformation, and fluid flow in the microfluidic channel is well maintained in both the deformed and recovered shapes. In addition, the shape fixing effect of the shape memory effect of SMPs under thermal stimuli enables them to return to their original shapes after structural deformation, and fluid flow in the microfluidic channel is well maintained in both the deformed and recovered shapes. In addition, the shape-fixing effect of SMPs to maintain a 3D shape allows the structure to stand freely without a substrate, and by introducing magnetic particles into the PDMS layer, the programming of the structure can be induced remotely and quickly through a portable magnet. Ng *et al.* fabricated a gel fiber with high flexibility, which was synthesized using a gel material partially substituted with ethylene glycol that can withstand the temperature required for the thermal curing of PDMS [Figure 10E][238]. The gel template, which is not adhesive to PDMS, could be easily removed by manually pulling without distorting the microchannel. The thermal replication molding of PDMS allowed the production of microchannels and demonstrated various 3D structures, including bifurcating junction, helical and weave networks, and microchannels with different cross sections, by manipulating the gel matrix.

CONCLUSION AND OUTLOOK

This review summarizes recent advances in various advanced material systems based on flexible/stretchable 3D structures. The design of 3D systems with flexibility and stretchability beyond conventional planar systems has enabled the exploration of various application options for target geometries with high complexity. As demonstrated by the examples presented in this review paper, these superior material systems with novel capabilities can provide new application concepts in widespread fields ranging from electronics, optoelectronics, energy devices, biomedical devices, sensors, actuators, and metamaterials to microfluidic systems. Although each of the technologies discussed in this article has unique functionality and outstanding performance, there are still areas that can be improved.

First, maintaining the unique functions via 3D geometry depends on structural stability against external stimuli, such as temperature changes, rain, and vibration. Understandably, there are a number of related challenges. Materials that use light to trigger the reconfiguration of 3D structures generally exhibit low thermal stability, so the discovery of active materials that respond only to single stimuli is expected to play an important role in improved mechanical stability. In addition, 3D structures consisting of ultra-thin film scaffolds may have difficulty maintaining their structure in harsh environments. The mechanical stability may be improved by introducing a support layer through methods such as initiated chemical vapor deposition (iCVD). 3D structures made of non-stretchable materials that are affected by vibration or wind will require a high level of energy dispersion in their structural design to resist external forces. There are also several improvements required in terms of applicability. For example, chip-level applications via 3D assembly at the nanoscale have been realized, but devices with high chip integration density have rarely been reported. In addition, the resulting yield and success rate of 3D structure fabrication must be further improved to meet the requirements of device mass production.

In this respect, further advances in 3D structure manufacturing technologies will pave the way for the development of devices with novel functions and improved performance. For 3D printing technologies that provide a high level of geometry control, it will be necessary to expand accessibility to high-performance materials and increase processing speed. Origami and kirigami methods, which operate at high speed under systematic rules, require new schemes to avoid manual intervention that hinders the realization of structural complexity and functionality at the micro and nanoscale. Finally, design capabilities for mapping 3D structures to 2D precursors in mechanically-guided assemblies are in the early stages of development, and design rules for more complex geometries are required. As a result, the application fields for 3D structures with flexibility and stretchability are also expected to expand as the manufacturing technology of 3D structures develops. For example, electronics embedded with 3D structures will create a variety of design opportunities that are lacking in 2D electronics within electrical engineering. In addition, the development of 3D multifunctional devices in the biomedical field will provide opportunities for research and clinical medical device development. These devices will also serve as a growth platform for the development of new research tools enabling material science exploration and discovery. Therefore, developing flexible/stretchable 3D structures will allow for novel research in many fields of study and will lead to unprecedented engineering applications.

The impressive advances outlined in this review will provide a strong incentive for research related to applications that can benefit from or are activated by 3D geometry. Furthermore, the question of how 3D structures can be utilized will shift to how they can be integrated further with various engineering fields, including electrical engineering, mechanical engineering, chemical engineering, cell biology, and biomedical engineering, to open new application areas.

DECLARATIONS

Authors' contributions

Supervised the overall direction and edited the manuscript: Kim BH
Configured the figure set and wrote the manuscript: Kim JH, Lee SE

Availability of data and materials

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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