
1

NATURE-INSPIRED STIMULI-RESPONSIVE SELF-FOLDING MATERIALS

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1.1 INTRODUCTION

Engineering of complex 3D constructs is a highly challenging task for the development of materials with novel optical properties, tissue engineering scaffolds, and elements of micro and nanoelectronic devices. Three-dimensional materials can be fabricated using a variety of methods including two-photon photolithography, interference lithography, molding [1]. The applicability of these methods is, however, substantially limited. For example, interference photolithography allows fabrication of 3D structures with limited thickness. Two-photon photolithography, which allows nanoscale resolution, is very slow and highly expensive. Assembling of 3D structures by stacking of 2D ones is time-consuming and does not allow fabrication of fine hollow structures.

Fabrication of 3D microobjects using controlled folding/bending of thin films—self-folding films—is novel and a very attractive research field [1, 2]. Self-folding films are the examples of biomimetic materials [1]. Such films, on the one hand, mimic movement mechanisms of plants [3] and, on the other hand, are able to self-organize and form complex 3D structures. The self-folding films consist of two materials with different properties. At least one of these materials, active one, can change its volume. Because of the non-equal expansion of the materials, the self-folding films are able to form a tubes-, capsules- or more complex-structure. Similar to origami, the self-folding films provide unique possibilities for the straightforward

Intelligent Stimuli-Responsive Materials: From Well-Defined Nanostructures to Applications, First Edition.
Edited by Quan Li.
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2 NATURE-INSPIRED STIMULI-RESPONSIVE SELF-FOLDING MATERIALS

fabrication of highly complex 3D micro-structures with patterned inner and outer walls that cannot be achieved using other currently available technologies. The self-folded micro-objects can be assembled into sophisticated, hierarchically organized 3D super-constructs with structural anisotropy and highly complex surface patterns. Until now most of the efforts were focused on the design of inorganic self-folding films [4]. On the other hand, due to their rigidity, limited biocompatibility, and non-biodegradability, application of inorganic self-folding materials for biomedical purposes is limited. Polymers are more suitable for these purposes. First, there are many polymers changing their properties in physiological ranges of pH and temperature as well as polymers sensitive to biochemical process [5]. Second, polymers undergo considerable and reversible changes of volume that allows the design of a variety of actively moving microconstructs [6]. Third, there are a variety of biocompatible and biodegradable polymers [7]. This chapter overviews recent progress in development of the polymer films which are able to fold and form 3D microstructures.

1.2 DESIGN OF SELF-FOLDING FILMS

Bending is essentially required for design of self-folding films and allows conversion of semi one-dimensional and two-dimensional objects into 2D and 3D ones, respectively. Typically, bending is the result of either expansion or contraction of a material caused by change of environmental conditions. In most cases, change of conditions, however, results in homogenous expansion or contraction in all directions and does not lead to increase of dimensionality. Bending is produced as a result of inhomogeneous expansion/shrinking, which occurs with different magnitudes in different directions. Bending could be achieved either (i) by applying gradients of field to homogenous materials or (ii) by applying non-gradient stimuli to inhomogeneous materials. The example of the first case is the bending of polyelectrolyte hydrogel during electrolysis [8]. The examples of the second case are the bending of liquid crystalline films [9], hydrogel with the lateral gradient monomer concentration [10], cantilever sensors [11], and shape-memory polymers [12].

In fact, design of self-folding objects using homogenous materials is technically very complicated because a very complex spatial force gradient must be formed and kept for a considerable period of time. For example, this can be achieved using surface tension by depositing a water droplet on a thin film [13]. The film folds immediately after the droplet is deposited. The formed 3D object changes its shape during drying of the droplet and unfolds when water is completely evaporated. In physiological buffer environment, surface tension effects are, however, weak. Fabrication of self-folding objects using inhomogeneous films is more straightforward. The inhomogeneous films fold due to difference in the properties on constituting materials in pre-programmed manner, which is defined by the film structure/pattern.

To date, three general approaches for design of self-folding polymer films using inhomogeneous materials are reported (Fig. 1.1). First approach is based on shape-memory polymers, which are partially liquid crystalline with directional anisotropy of properties (Fig. 1.1a). At low temperature, the shape-memory materials are in their temporary shape. The films recover their permanent shape by heating. In second

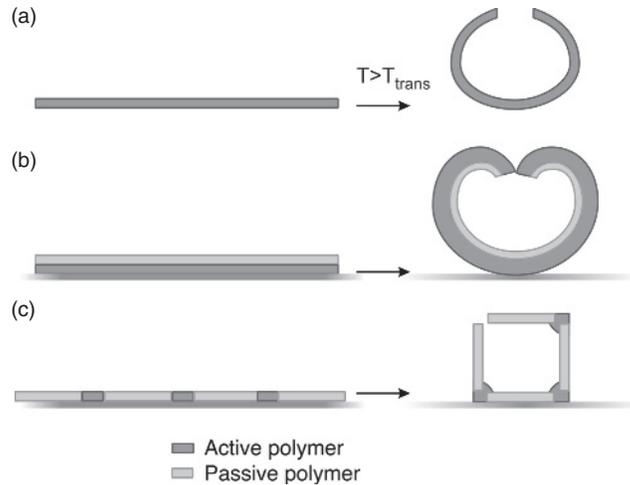


FIGURE 1.1 Approaches for design of self-folding polymer objects (a) relaxation of shape-memory polymers (b) folding of polymer bilayer due to expansion of one of the polymers (c) folding of patterned polymer film caused by shape change of one of polymers. Reproduced from Reference 14, with kind permission from Royal Society of Chemistry. Copyright 2011.

and third approaches, two polymers are used. One of the polymers is passive and its properties remain unchanged. Another polymer is active and its volume or shape is changed when stimulus is applied. The second approach is based on the use of polymer bilayers (Fig. 1.1b). Active polymer swells or shrinks in response to signal. The swelling in one direction is restricted by the passive polymer. As a result, the bilayer does not uniformly expand/shrink but it does fold and unfold. Third approach is based on the use of patterned film of passive polymer with insertion of the active one (Fig. 1.1c). Active polymer undergoes shape transition, which might be caused by surface forces, that results in folding of the film.

1.3 MECHANISM OF FOLDING

Timoshenko [15] was the first who investigated bending of bilayer, which consist of two materials with different expansion coefficients. He assumed that the bilayer can bend in only one direction and results in a bilayer with uniform curvature

$$\frac{1}{\rho} = \frac{6(\epsilon_2 - \epsilon_1)(1 + m)^2}{h \left(3(1 + m)^2 + (1 + mn) \left(m^2 + \frac{1}{mn} \right) \right)} \quad (1.1)$$

$$\frac{E_1}{E_2} = n \quad (1.2)$$

$$\frac{a_1}{a_2} = m \quad (1.3)$$

4 NATURE-INSPIRED STIMULI-RESPONSIVE SELF-FOLDING MATERIALS

where E are the elasticity modulus, a are the thickness of the layers, h is the total thickness ($h = a_1 + a_2$), ε is the stress of the films, ρ is the radius of curvature. As it comes from the Equations (1.3), radius of curvature is inversely proportional to film stress. Moreover, radius of curvature first decrease and then increase with the increase of m . The resultant curvature is not very sensitive to the difference in stiffness between the two layers, and is mainly controlled by the actuation strain and the layer thickness. The Timoshenko equation applies to a beam bending in only one direction and does not predict the folding direction. Moreover, Timoshenko equation considers elastic deformations, the polymers and hydrogels often demonstrate viscoelastic properties.

More recent models have considered complex bending of bilayer in two dimensions. Mansfield found analytical solutions for large deflections of circular [16] and elliptical [17] plates having lenticular cross sections with a temperature gradient through the thickness. For small gradients, the plates formed spherical caps, curved equally in all directions. At a critical gradient, a configuration with greater curvature in one direction became more favorable. Because of the lens-shaped thickness profile, even though the elliptical plate had a major axis it showed no preferred direction for bending even for large deflections. Freund determined the strain at which the spherical cap, formed by circular bilayer of uniform thickness, becomes unstable using low order polynomial solutions and finite element simulations [18].

Later, Smela et al. showed that short-side rolling was preferred in the case of free homogeneous actuation and that this preference increased with aspect ratio (ratio of length to width of rectangular pattern) [19]. Li et al. [20] and Schmidt [21] experimentally demonstrated the opposite scenario, namely a preference for long-side rolling, in the case where bilayers are progressively etched from a substrate. They observed that when the tube circumference was much larger than the width or the aspect ratio of the rectangle was high, rolling always occurred from the long side. When the tube circumference was much smaller than the width and the aspect ratio of the membrane pattern was not very high, the rolling resulted in a mixed yield of long- and short-side rolling, as well as a “dead-locked turnover” shape. Short-side rolling occurred at small aspect ratios when the deformed circumference is close to the width. In these self-rolling systems, the active component undergoes relatively small volume changes or actuation strains, which are nearly homogenous over the whole sample. Control of rolling/folding direction is very important for programmed folding. For example, Schmidt demonstrated that introduction of wrinkles allows switching to short-side rolling [21].

In inorganic self-rolling systems, the active component undergoes relatively small volume changes or actuation strains, which are nearly homogenous over the whole sample. Hydrogels, however, demonstrate considerably different properties. First, hydrogels undergo large volume changes (up to 10 times) upon swelling and contraction. Second, the swelling of a hydrogel is often kinetically limited: due to slow diffusion of water through hydrogel, the parts which are closer to the edges swell first while the parts which are closer to the center of the films swell later. Stoychev et al. investigated the folding of rectangular stimuli-responsive hydrogel-based polymer bilayers with different aspect ratios and relative thicknesses placed on a substrate

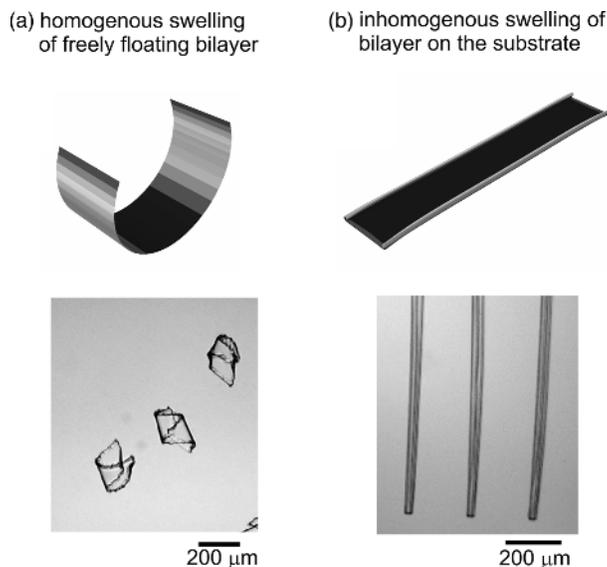


FIGURE 1.2 Simulation and experimentally observed folding of rectangular bilayers at different conditions: (a) freely floating rectangular bilayer (homogenous swelling) (b) rectangular bilayer on substrate (inhomogeneous swelling) Reproduced from Reference 23, with kind permission from American Chemical Society. Copyright 2012.

and freely floating is fluid [22]. The polymer bilayer with homogenous actuation which freely floats in aqueous medium undergoes short-side rolling leading to the formation of scrolls (Fig. 1.2a). In the case of bilayer placed on a substrate, it was found that long-side rolling dominates at high aspect ratios (ratio of length to width) when the width is comparable to the circumference of the formed tubes, which corresponds to a small actuation strain (Fig. 1.2b). Rolling from all sides occurs for a higher actuation strain, namely when the width and length considerably exceed the deformed circumference. In the case of moderate actuation, when the width and length are comparable to the deformed circumference, diagonal rolling is observed. Short-side rolling was observed very rarely and in combination with diagonal rolling. Based on the experimental observations, finite-element modeling as well as energetic considerations, it was argued that bilayers placed on a substrate start to roll from corners due to quicker diffusion of water. Rolling from the long side starts later but dominates at high aspect ratios in agreement with energetic considerations. It was showed experimentally and by modeling that the main reasons causing a variety of rolling scenarios are (i) non-homogenous swelling due to the presence of the substrate and (ii) adhesion of the polymer to the substrate.

There are many parameters which determine folded shape. For example, the shape of formed 3D object depends on the shape of the polymer films (Fig. 1.3). The simplest case of self-folding object is a tube which is formed by rectangular bilayers [24]. Helixes of different kinds are formed by polymer bilayers with the gradually

6 NATURE-INSPIRED STIMULI-RESPONSIVE SELF-FOLDING MATERIALS

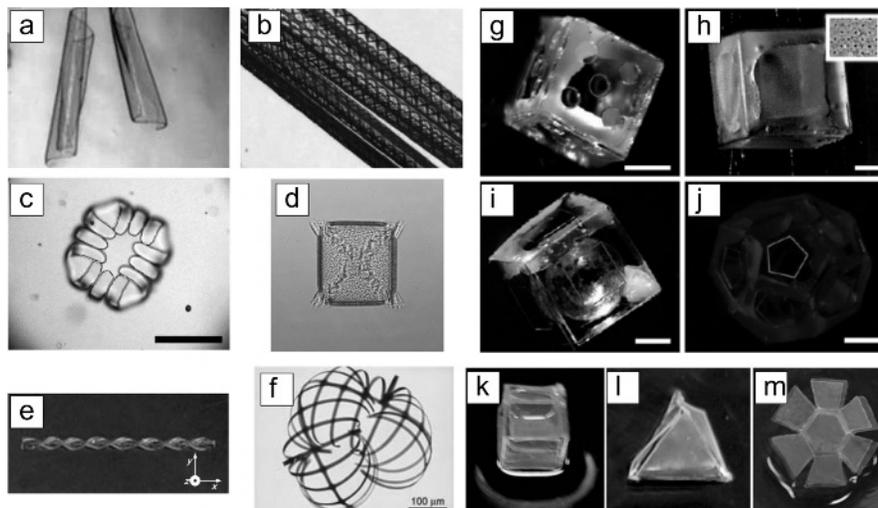


FIGURE 1.3 Examples of self-folding polymer films: (a), (b) tubes. Reproduced from References 24b, with permission from RSC, Copyright 2010, 24c, with permission from Wiley, Copyright 2005. (c,d) capsules. Reproduced from References 24f, 26, with permission from Wiley-VCH Verlag GmbH & Co. KGaA. Copyright (e) helix. Reproduced from References 25, 26, with permission from Royal Society of Chemistry, Copyright 2011. (f) hierarchically shaped tube. Reproduced from Reference 28, with permission from Royal Society of Chemistry. Copyright 2011. Reproduced from Reference 28, with permission from Wiley-VCH Verlag GmbH & Co. KGaA. Copyright 2011 (g), (h), (i), (k) cubes with porous walls. Reproduced from References 25, 27b, with kind permission from Springer Science & Business Media. Copyright 2010. (j) dodecahedron. Reproduced from Reference 27b, with kind permission from Springer Science & Business Media. Copyright 2010. (k) Reproduced from Reference 25, with permission from Royal Society of Chemistry. Copyright 2011. (l) pyramide. Reproduced from Reference 25, with permission from Royal Society of Chemistry. Copyright 2011. (m) phlat ball. Reproduced from Reference 25, with permission from Royal Society of Chemistry. Copyright 2011.

changing ratio between polymers [25]. Envelope-like capsules with rounded corners or nearly spherical ones are formed the star-like polymer bilayers with four and six arms, respectively [24f, 24g, 26]. In these examples, simple rounded figures based on different combinations of fully or semi-folded tubes are formed. Moreover, because of the isotropy of mechanical properties of the bilayer, formation of hinges during folding of bilayers is considered to be impossible. Objects with sharp edges are formed patterned bilayer where active component is deposited locally. The active component can either swell/shrink or change its shape due to melting. In this way, cubes and pyramids are formed by patterned bilayer with the active junction elements [25, 27]. Important, in all reported cases, folding runs in one step—active polymer changes its volume that results in simple bending.

1.4 FABRICATION OF SELF-FOLDING FILMS

The polymer films with different shape can be obtained either by cutting [24a–c], using microwell-like substrates [24e–g] or photolithography [24d, 26, 27]. Cutting allows fabrication of millimeter large species with the rectangular shape, which form the tubes. The main advantage of this method is simplicity and applicability to almost all combinations of crosslinkable polymers. Use of microwell-like substrates is technically more complicated but allows fabrication of polymer layers with different shapes such as rectangles or stars. Photolithography of bilayers allows large scale fabrication of self-folding objects of different shape and size starting from several microns. The formed self-folding objects have rounded corners. The main disadvantage of this approach is necessity to choose proper solvents for polymer deposition in the way that the first polymer is not dissolved during deposition of the second polymer. Fabrication of patterned polymer films is the technically most complicated procedure and requires mask alignment during several steps of photolithography. On the other hand, it allows fabrication of the broadest range of shapes of self-folding objects.

1.5 STIMULI-RESPONSIVE PROPERTIES OF SELF-FOLDING FILMS

Use of polymer sensitive to different signals allows design of self-folding films folding upon immersion in solvent, change of pH, temperature, electric or biochemical signals.

1.5.1 pH Responsive

Self-folding films sensitive to pH are commonly designed using weak polyelectrolytes as active polymers. Luchnikov demonstrated that polystyrene-poly(4 vinyl pyridine) bilayer [24c] as well as polystyrene-poly(4 vinyl pyridine)-polydimethylsiloxane trilayer [29] are able to roll at low pH when poly(4-vinylpyridine) is protonated and swells in water. Use of layers with 2D gradient of thickness allowed thorough investigation of folding [30]. It was found that rate of rolling increased with the acidity of the solution. Tube diameter and rate of rolling decreased with the increase of the UV exposure time. Moreover, increase of thickness of PS results in increase of the diameter of tube.

Lee et al. used pH sensitive poly(methacrylic acid)-poly(2-hydroxyethyl methacrylate) [24e] and poly(methacrylic acid) (PMAA)/polyEGDMA [24g] patterned bilayer which folds in contact with biological fluids. It was not shown that the folding depends on pH. However, since weak polyelectrolyte poly(methacrylic acid) was used, the systems are expected to respond to pH signal. Gracias et al. fabricated millimeter large polyethylene glycol/poly-(*N*-isopropylacrylamide – acrylic acid) bilayers which are able to snap in response to pH signal [27a]. One can also expect that this system is thermoresponsive. Huck et al. reported pH responsive gold-poly(methacryloxyethyl trimethylammonium chloride) brush patterned films which fold in response to change of pH and salt concentration [28].

1.5.2 Thermoresponsive

Thermoresponsive self-folding films can be designed using continuous thermal expansion, melting, shape-memory transition or polymers which demonstrate LCST (Low Critical Solution Temperature) behavior in solutions. Kalaitzidou et al. used continuous volume expansion with temperature and demonstrated thermoresponsive rolling-unrolling of polydimethylsiloxane–gold bilayers tubes at 60–70 °C [24a, 24b] which is due to different temperature expansion coefficients.

Gracias et al. used melting of polymer, which form a droplet and forces patterned polymer films to fold. This was demonstrated on the example of patterned SU-8 photoresist–polycaprolactone film, which irreversibly folds at 60 °C [31] due to melting of polycaprolactone (Fig. 1.4). In order to reduce the transition temperature and make film more suitable bio-related applications, Gracais et al. used photoresist hinges which are sensitive to temperature around 40 °C [32]. The metal-polymer grippers irreversibly fold in response to temperature as well.

Lendlein et al. demonstrated the possibilities to design thermoresponsive macroscopic self-folding objects using shape-memory polymers based on different poly(ϵ -caprolactone) [12]. At low temperature, the materials are in their temporary shape. The films recover their permanent shape and irreversibly fold by heating, which could be accompanied by a change of transparency.

Polymer bilayers, where active component is thermoresponsive poly-(*N*-isopropylacrylamide)-based copolymers, are more suitable for encapsulation of cells.

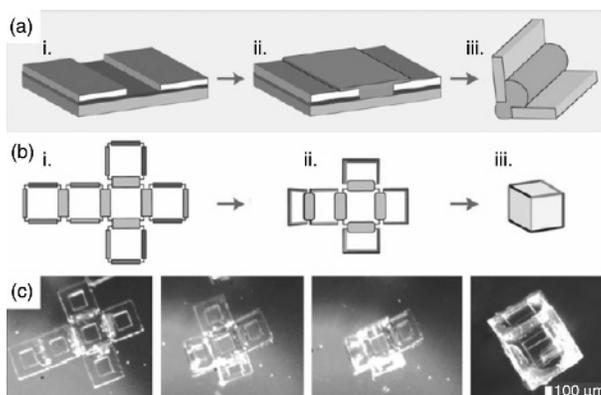


FIGURE 1.4 Thermoresponsive self-folding SU-8-polycaprolactone thin films. (a) fabrication: (i) A sacrificial layer was spin coated on a clean Si wafer. SU-8 panels were patterned using conventional photolithography. (ii) PCL was deposited in hinge gaps. (iii) 2D templates were lifted off via dissolution of the PVA layer in water and self-assembly occurred on heating above 58 °C. (b, i–iii) Schematic demonstrating self-folding of a cubic container. External “locking” hinges are colored in pairs to denote corresponding meeting edges. (c) Video capture sequence (over 15 s) showing a 1 mm sized, six-windowed polymeric container self-folding at 60 °C. Reproduced from Reference 27b, with kind permission from Springer Science & Business Media. Copyright 2010.

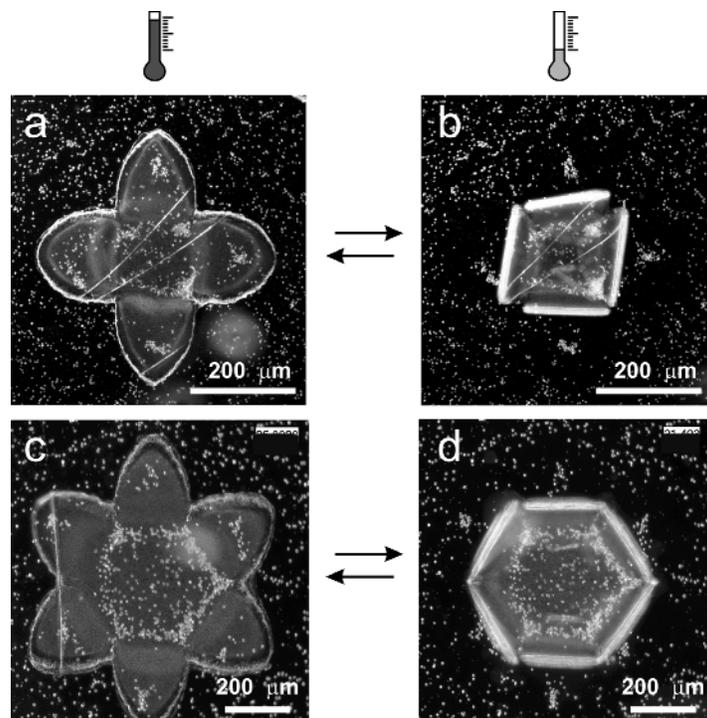


FIGURE 1.5 Encapsulation of yeast cells inside thermoresponsive poly-(*N*-isopropylacrylamide)-polycaprolactone self-folding capsules. Yeast cells are adsorbed on the polymer bilayer at elevated temperature. Cooling leads to swelling of the thermoresponsive polymer and folding of the capsules. Second heating results in unfolding of the capsules and release of the cells. Reproduced from Reference 26, with permission from Royal Society of Chemistry. Copyright 2011.

In aqueous media, poly-(*N*-isopropylacrylamide)-based hydrogels reversibly swell and shrink below and above 33 °C. Moreover, the temperature of transition between swollen and shrunk states can be tuned by proper selection of composition of copolymer. As a result, poly-(*N*-isopropylacrylamide)-polycaprolactone patterned bilayers fold and unfold forming tubes of capsules below and above this temperature, respectively (Fig. 1.5) [24d, 26].

1.5.3 Light Responsive

Light based on light-to-heat conversion [33]. In the first approach, carbon nanotubes (CNTs) were incorporated inside thermoresponsive poly(*N*-isopropylacrylamide) hydrogel. Light is absorbed by CNTs and converted into heat. The increase of temperature leads to deswelling of the hydrogel and unfolding of the 3D structure [33a]. In the second approach, pre-strained polystyrene (also known as Shrinky-Dinks) that

10 NATURE-INSPIRED STIMULI-RESPONSIVE SELF-FOLDING MATERIALS

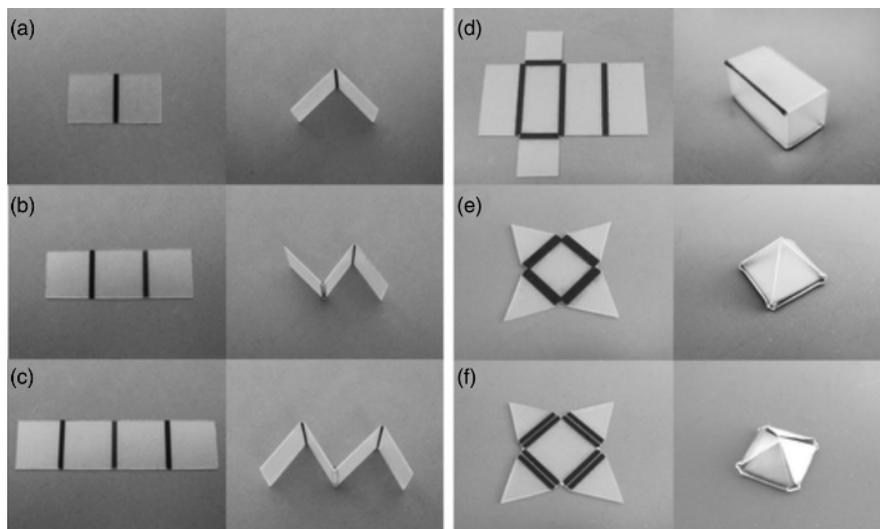


FIGURE 1.6 Photographs of 3D structures created by self-folding of Shrinky-Dinks patterned with a desktop printer. (a) Single line patterned on the top side of the Shrinky-Dink; (b) two lines patterned on either side of the Shrinky-Dink; (c) three lines patterned on alternating sides of the Shrinky-Dink; (d) rectangular box; (e) tetrahedral box; and (f) tetrahedral box with adjacent double hinges. Reproduced from Reference 33b, with permission from Royal Society of Chemistry. Copyright 2011.

shrink in-plane if heated uniformly was used (Fig. 1.6) [33b]. Black ink patterned on either side of the polymer sheet provides localized absorption of light, which heats the underlying polymer to temperatures above its glass transition. At these temperatures, the predefined inked regions (i.e., hinges) relax and shrink, and thereby cause the planar sheet to fold into a 3D object. Self-folding is therefore achieved in a simple manner without the use of multiple fabrication steps and converts a uniform external stimulus (i.e., unfocused light) on an otherwise compositionally homogenous substrate into a hinging response.

1.5.4 Solvent Responsive

Most examples of solvent-responsive self-folding films are the films, which fold upon immersion in aqueous media. Such films contain water-swelling uncharged polymers. Lee fabricated partially biodegradable polyvinyl alcohol-chitosan [24f] and chitosan-poly(PEGMA-co-PEGDMA) bilayers [24g] which folds in water due to swelling of polyvinyl alcohol and polyethylene glycol, respectively. Jeong and Jang et al. developed the approach for fabrication of millimeter size self-folding objects which are able for fold and form different 3D objects such as tube, cube, pyramids and helices [25]. Water-swelling polydimethylsiloxane-polyurethane/2-hydroxyethyl methacrylate complex bilayers and patterned films were used. Since

poly(vinyl alcohol), polyethylene glycol and poly (2-hydroxyethyl methacrylate) and are not polyelectrolytes, the swelling is expected to be independent of pH of aqueous media. These systems immediately fold upon immersion in aqueous media that hampers loading of cells. Huck reported the example of the system which folds in methanol. This system is based on poly(glycidyl methacrylate) brush layer grafted to gold patterned films [28].

1.5.5 Other Stimuli

Except for pH-, thermo- and solvent-responsive systems, there are also several examples of systems, which fold in response to other stimuli such as presence of enzymes or applied electric field. Smella [4a] and Jager et al. [4b], who introduced the self-folding films, demonstrated folding and unfolding of patterned gold film with polypyrrole hinges in the response to electric signal. Whilesides et al. fabricated electro-responsive self folding bilayer, which consists of polydimethylsiloxane with the aligned cardiomyocytes [34]. The polymer-cell film adopted functional 3D conformations when electric signal is applied. These centimeter-scale constructs perform functions as diverse as gripping, pumping, walking, and swimming with fine spatial and temporal control.

Enzyme-sensitive self-folding films were developed for the first time by Gracias et al. The approach is based on use of self-folding metallic grippers with active polymer hinges, which are sensitive to presence of enzymes [35]. Two kinds of biodegradable polymer were used. The gripper, which is unfolded in initial state, folds when first polymer is degraded after addition of first enzyme. The gripper unfolds when second enzyme is added and second polymer is degraded. As result one circle of folding and unfolding is achieved.

1.6 PROPERTIES AND APPLICATIONS OF SELF-FOLDING FILMS

The one field of application of self-folding polymer thin films is the controlled encapsulation and release of drugs, particles and cells. Kalaitzidou demonstrated reversible adsorption-desorption of fluorescently labeled polyethylene glycol, which is considered as model drug, inside PDMS-gold tubes at 60–70 °C [24a]. Gracias et al. demonstrated irreversible encapsulation of yeast cells inside self-folding SU8-PCL films upon heating above at 60 °C [31]. Poly-(*N*-isopropylacrylamide)-based self-folding films were also demonstrated to be suitable for reversible encapsulation of particles and yeast cells [24d, 26]. Cells were encapsulated upon cooling below 30 °C and could be released from the film, which is unfolded above 30 °C. This encapsulation and release is completely reversible and could be repeated many times. Very recently, fully biodegradable self-folding films, which consist of commercially available biodegradable polymers, were also used to encapsulate cells (Fig. 1.7a) [36]. In fact there are many approaches which can be used for encapsulation of cells including LbL, microfluidic technique, and controlled precipitation. The advantage

12 NATURE-INSPIRED STIMULI-RESPONSIVE SELF-FOLDING MATERIALS

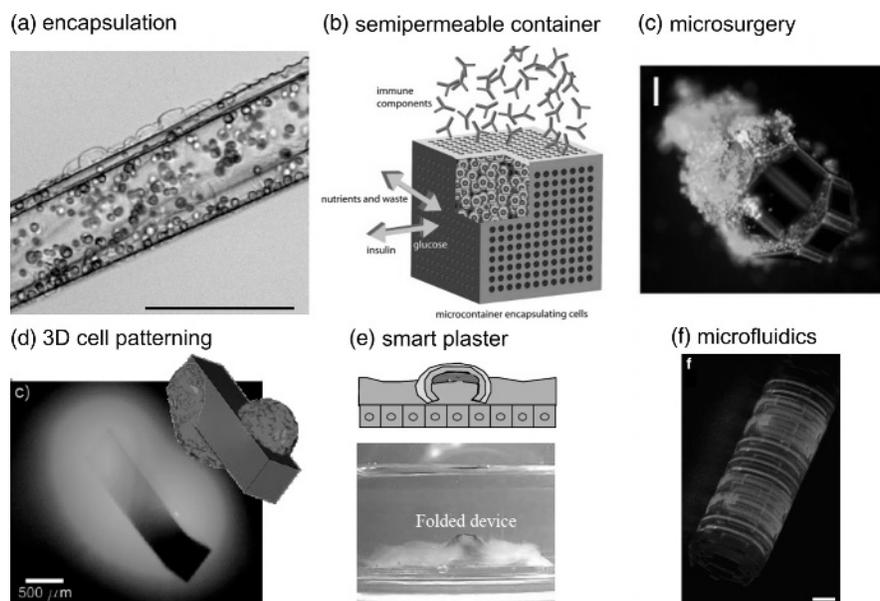


FIGURE 1.7 Examples of biomedical applications of self-folding films: (a) yeast cells encapsulation inside fully biodegradable self-rolled film (Reprinted with permission from Reference 36. Copyright 2011 American Chemical Society), (b) scheme of artificial pancreas based on nanoporous self-folded devices: glucose and oxygen can penetrate through the pores of the folded device with encapsulated pancreas cell while immune components are unable to penetrate (Reprinted with permission from Reference 37. Copyright 2011 Elsevier), (c) self-folding microgripper with tissue (Reprinted with permission from Reference 32c. Copyright 2009 PNAS), (d) 3D cellular pattern produced by controlled diffusion of chemical through pores of self-folded object (Reprinted with permission from Reference 38. Copyright 2002 Wiley-VCH Verlag GmbH & Co. KGaA), (e) smart plasters which direct diffusion of drugs and prevent their leakage (Reprinted with permission from Reference 24e. Copyright 2006 Elsevier), (f) 3D microfluidic device obtained by folding (Reprinted with permission from Reference 39. Copyright 2011 Nature Publishing Group).

of self-folding approach is possibility of reversible encapsulation and release. Self-folded objects with nanoporous walls and encapsulated cells were suggested as prototype of artificial pancreas. The small molecules such as glucose and dissolved oxygen are able to pass through the pores while larger ones such as antibody are unable to do it. This size-selective permeability of self-folded capsules allows avoiding immune response that is highly demanded during transplantation of pancreas cells (Fig. 1.7b) [37]. Gracias et al. used rigid metal-made self-folding microgrippers for capturing pieces of tissues and their controlled transport (Fig. 1.7c). Such systems are particularly attractive for non-invasive biopsy [32c]. Self-folded objects were used as scaffolds for fabrication of 3D cellular constructs (Fig. 1.7d) [4i, 4j]. Controlled release of small molecules through the pores of self-folded microconstructs was used to spontaneously organize cells in 3D environment [38].

Self-folding films can also be used as smart plasters (Fig. 1.7e). Lee demonstrated this concept on the example of millimeter size poly(methyl methacrylate)–poly(2-hydroxyethyl methacrylate) bilayer with attached mucoadhesive drug layer. The non-swelling PHEMA layer serves as a diffusion barrier, minimizing any drug leakage in the intestine. The resulting unidirectional release provides improved drug transport through the mucosal epithelium. The functionality of this device is successfully demonstrated in vitro using a porcine small intestine [24e].

There are several non-biorelated examples of application of self-folding polymer films. Deposition of patterned metal on the polymer bilayer allowed fabrication of self-rolled tubes with patterned conductive inner wall [24c]. In another example, pyrolysis of polystyrene-poly(4-vinyl pyridine)-polydimethylsiloxane trilayer [29] were used for fabrication of silica tubes. Gracias used self-folding polymers films were used to fabricate self-assembled curved microfluidic networks (Fig. 1.7f) [39].

1.7 CONCLUSIONS AND OUTLOOK

Self-folding polymeric thin films are emerging, but this is a rapidly developing field. There are many examples of the polymer thin films folding due to immersion in solvents, change of pH, temperature, light, electric signal or presence of enzymes. The self-folding films are particularly promising for design of biomaterials, controlled encapsulation and release of drugs and cells. Here, cells are not locked inside amorphous and densely crosslinked matrix, as it happens in the case of hydrogels, but are free to move. Moreover, self-folding films are highly promising for design of smart actuating systems for in vivo application and elements of flexible organic electronics. In future the efforts may be focused on development of biomimetic polymer materials, which can be completely integrated into living organisms and be controlled by them.

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14 NATURE-INSPIRED STIMULI-RESPONSIVE SELF-FOLDING MATERIALS

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16 NATURE-INSPIRED STIMULI-RESPONSIVE SELF-FOLDING MATERIALS

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