J Mater Sci (2010) 45:2543–2552
DOI 10.1007/s10853-010-4237-6

REVIEW

DNA self-assembly: prospectus and its future application

Sathya Sadhasivam · Kyu Sik Yun

Received: 9 November 2009 / Accepted: 12 January 2010 / Published online: 26 January 2010

Abstract The field of DNA nanotechnology has grown rapidly in the past 10 years, with many baby steps and exciting breakthroughs. DNA has recently been emerged as a versatile material for constructing artificial molecular structures and strategy which has excellent intrinsic characteristics, including programmability, self-organization, molecular recognition, and molecular-scale structuring properties, makes it an attractive nanoscale building material. Excitingly, DNA can be considered as a natural candidate for molecular self-assembly. In this review, we have focused on the methods for DNA self assembling patterns within the molecular fabric of DNA lattices.

Introduction

Nanotechnology is used for construction and exploitation of new materials at the nanoscale level to generate products that exploit novel properties. There has been emerging growth in this field with an increasing number of organizations developing novel materials and products. DNA nanotechnology is emerged from biology and nanotechnology which comprises biology and chemistry principles as well as the properties of DNA to construct nanostructured materials. DNA nanostructures have some exclusive advantages among nanostructures: they are relatively easy to design, fairly predictable in their geometric structures, and have been experimentally implemented in a growing number of labs around the world. These nanostructured materials have been utilized in many fields such as Engineering, Medicine, Health Care, Cell and Molecular Biology, and Optics and Electronics. Due to the variable properties and enormous capabilities of DNA, many new technologies would be emerged from DNA nanobiotechnology [1]. Recently, researchers have constructed primarily of synthetic DNA. A notable principle in the study of DNA nanostructures is the use of self-assembly processes to actuate the molecular self-assembly. Since self-assembly operates naturally at the molecular scale, it does not suffer from the limitation in scale reduction that so restricts lithography or other more conventional top–down manufacturing techniques. Moreover, other surveys of DNA nanotechnology and devices have been given by LaBean et al. [2], Jonoska and Rozenberg [3], Eshaghian-Wilner [1], and Seeman [4]. In this review we are focused on the DNA self assembling patterns within the molecular fabric of DNA lattices.

S. Sadhasivam · K. S. Yun (✉)
College of Bionanotechnology, Kyungwon University,
Gyeonggi-Do 461701, South Korea
e-mail: ykyusik@kyungwon.ac.kr

DNA self-assembly in molecular-scale devices

DNA is well characterized and universal which contains information in the nucleotide sequence. DNA may conduct one-dimensionally based on that sequence. The fundamental numerical and thermodynamic properties of DNA are well understood and can be designed by available software systems. For designing the DNA nanostructure or device, one plans to design a library of ssDNA strands with particular segments that hybridize to specific complementary segments on other ssDNA. There are a number of software systems for performing these combinatorial sequence design task and designing of DNA nanostructures with desired structures. There are many advantages of DNA as a material for building things at the molecular scale. The assembly of DNA nanostructures is an easy experimental

process: in many cases, one can be able to simply combine the various component of ssDNA into a single test tube with an appropriate buffer solution at a suitable temperature above the expected melting temperature of the most stable base-pairing structure, and then slowly cool down the test tube below the melting temperature [1]. The assembled DNA nanostructures can be characterized by a variety of techniques. One of them is electrophoresis. It provides information about the relative molecular mass of DNA molecules, in addition to some information regarding their assembled structures, depending on what type of electrophoresis is used. Moreover, other techniques like Atomic Force Microscopy (AFM) and Transmission Electron Microscopy (TEM) provide images of the actual assembled DNA nanostructures on 2D surfaces [1].

Self-assembled DNA nanostructures

Seeman et al. was the first to explore the self-complementarities of DNA for construction of novel nanostructures [5]. They succeeded in making branched junction motifs with multiple double-helical arms, such as the highly versatile four-arm junction. This construct reflects the Holliday junction, and in theory should assemble into quadrilateral lattices by sticky end cohesion [6, 7]. Interestingly, this four-arm branch motif can be stiffened once combined in pairs. Mao et al. [8], have fused four such junctions into a rhombus-like building block and successfully established its further assembly into 2D lattices (Fig. 1). Based on the idea of using immobile DNA junctions, a large number of distinct DNA building blocks

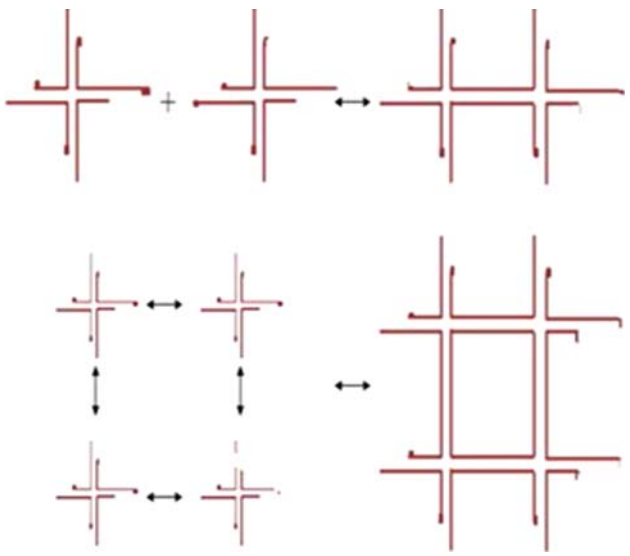

Fig. 1 Schematic representation of DNA tile-based self-assembly: combining branched DNA junction with sticky-end associations to self-assemble 2D lattices

(tiles) have been designed and experimentally inaugurated in the last two decades. Seeman et al. noted the construction of double crossover (DX) complexes, which consisted of two double helical domains joined together by two juxtaposed holiday junction-like crossover motifs [9]. Accurately designed sticky ends further facilitated the assembly into periodic 1D and 2D lattices [10]. A closely related motif combining a stem–loop hairpin with one of the duplex arms of DX (known as DX + J) was also reported [11]. The extra hairpin loop act as a topographical marker it is readily visible under Atomic Force Microscopy (AFM) [9, 12]. Seeman and coworkers have also reported to describe the generation of paranemic crossovers (PX) [13, 14] which arises from fusion of two parallel double helices by reciprocal exchange at every possible contact point. By regulating the inter conversion between a PX junction and its topoisomeric JX state, a robust DNA nanomechanical device was built [15, 16]. Structures with triangular building blocks have also been reported. In 1998, DX tiles were successfully fused to DNA triangles, as a consequence creating a unique zigzag pattern [17].

Triple crossover complex (TX) contained three helices and four crossovers. As in DX tiles, two adjacent helices have been connected by two four-arm junctions. Compared to DX tiles, TXs afford larger space and further extend the tool box of useful building block prototypes. LaBean and coworkers also reported a more complex planar building block [15, 18]. Further DNA motif, 4 × 4 cross tiles, consisting of four four-arm junctions was reported in 2003 (Fig. 2) [17]. Since the cross tile has a square aspect ratio and helix stacking in all four directions in the plane, they can assemble into very large 2D lattices. Two other triangle tile types can also be prototyped, which featured the formation of triangular and hexagonal patterns [19, 20].

Building blocks and their variants have also been used in the construction of self-assembled lattices. A variety of 2D periodic lattices, ribbons, and tubes have effectively demonstrated. Many complicated designs include double–double crossover [21] and 4-, 8-, and 12-helix DNA tile complexes [22], have also been used for assembly of planar and tubular structures. DNA tiles that hold their helices in non-planar domains 4 were prototyped by several groups although attempts at using them for 3D lattice assembly have yet to succeed [15, 23, 24].

Sharma et al. established the 3D nanoparticles assembly. DNA nanotubes formed through either self-association of multi-helix DNA bundles or the rolling of 2D DNA sheets, they formed a variety of gold nanoparticle architectures including single, double, and nestedspirals [25]. Interestingly, the nanoparticles were found to manipulate the conformations of the DNA nanotubes through size-dependent steric repulsion effects [26]. Designing of more complex assemblies of multi-component nanoscale

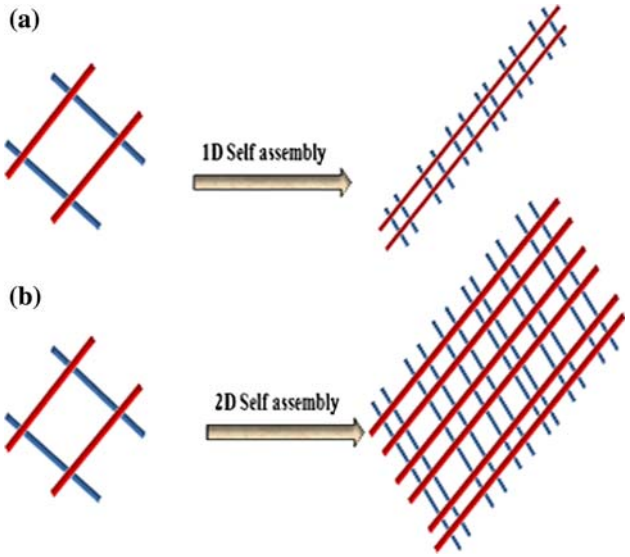

Fig. 2 Schematic representations of the molecular mechanism and their assembly. **a** One-dimensional self-assembly of the design into an array. **b** Two-dimensional self-assembly produces a lattice work of DNA. The array shows the 2D self-assembly product of the motif; the long separations between helices contain four helical turns, and the short separations contain two helical turns

materials was described by the LaBean group [27]. DNA-based nanofabrication is used to produce self-assembling nano electronic circuits that incorporate carbon nanotubes, metal nanoparticles, and semi-conductor quantum dots.

The ability of DNA to self-assemble into one-, two- and three-dimensional nanostructures [5–28], combined with the precision that is now possible when positioning nanoparticles [29, 30] or proteins [15–31] on DNA scaffolds, provide a promising approach for the self-organization of composite nanostructures [32, 33]. Predicting and controlling the functions that emerge in self-organized biomolecular nanostructures is a major challenge in systems biology, and although a number of innovative examples have been reported [34, 35].

The emergent properties of systems in which enzymes are coupled together have been explored. Recently Wilner et al. reported the self-assembly of a DNA scaffold made of DNA strips that include 'hinges' to which biomolecules also be tethered. They attach either two enzymes or a cofactor–enzyme pair to the scaffold, and show that enzyme cascades or cofactor-mediated biocatalysis can proceed effectively; similar processes are not observed in diffusion-controlled homogeneous mixtures of the same components. Furthermore, because the relative position of the two enzymes or the cofactor–enzyme pair is determined by the topology of the DNA scaffold, it is possible to control the reactivity of the system through the design of the individual DNA strips. This method could lead to the self-organization of complex multi-enzyme cascades [36].

DNA as building block for self-assembly

In 1982 Seeman proposed self-assembled nanostructures with DNA as building blocks. Building block is defined as a block of material to construct to use [5]. There are different kinds of bio-bonds available. It is divided into three types:

(1) ssDNA/ssDNA interaction, which is also renowned as DNA hybridization.
(2) Protein/dsDNA interaction: proteins are able to interact with double helix of DNA. One of them is Polymerase that opens the double helix for DNA replication.
(3) Protein/protein interaction: it is also called docking. The attraction is specific because of proteins 3D conformation compatibility [37].

DNA consists of two long polymers of simple units called nucleotides, which are made up of sugars and phosphate groups joined by ester bonds. These two strands run in opposite directions to each other and are therefore anti-parallel. Attached to each sugar is one of four types of molecules called bases. DNA hybridization process is one of the major tool for micro and nano-scale self-assembly. DNA hybridization has been used for a long time in DNA micro-arrays. These micro-arrays have been designed for gene expression experiments, and can express thousands of genes with a single array [38, 39]. Electrostatic forces play the major role in DNA hybridization the method relies on strong Coulomb forces to bring complementary parts together. Oligonucleotide is referred to as short DNA sequence. These controlling parameters define hybridization as a deterministic process. This biological process is controlled by some key parameters like temperature, which is the most important controlling hybridization parameter [38, 40]. Sequence of DNA [41] and its complexity, along with its length, number of G–C pairs present in the DNA helix [38, 42], ionic composition of the solution [32, 38, 43].

DNA microarray is one of the powerful tool. Self-assembly is depending on the DNA micro-arrays principle, complementary single DNA strands, each one attached on any one of the to be assembled components, or to a component and its desired location on the substrate. The complementary strands of DNA will find each other and bond when floating in proximity, consequently attaching the nano particle to the substrate of to its counterpart. The success of proposed process, and ultimately, its achievability requires the knowledge of the mechanical interaction between complimentary strands. Biologically many models have been proposed to optimize the hybridization results, especially on DNA micro arrays, but all have been purely based on thermodynamic and statistic approaches,

thus they are described in terms of interaction energy. Besides, the expression of this interaction energy differs greatly depending on the used approach and there are not any insignificant links to obtain the magnitude of the interaction force. In addition to the knowledge of the interaction force between DNA strands, it is also needed to explore the attachment between an inorganic material and a DNA strand [37].

Attachment of DNA to surfaces

Attachment of DNA to surfaces has focused on the direct bonding of alkenes containing functional groups, such as esters, acids [44, 45], and chlorides [46] to hydrogen-terminated silicon surfaces. The initial step in the direction of DNA-based nanotechnology is to attach DNA molecules to surfaces. Still now, the most widely used attachment scheme utilizes the covalent bond between sulfur and gold [47–49]. Nuzzo and Allara were the first to find out the formation of long chain ω-substituted dialkyldisulfide molecules on a gold substrate [48]. Bain et al. [49] have established a new model system consisting of long-chain thiols that adsorb from solution onto gold to form densely packed, oriented monolayers. The bonding of the sulfur head group to the gold substrate is in the form of a metal thiolate, which is a very strong bond ($\sim$44 kcal/mol), and hence the resulting films are quite stable and very suitable for surface attachment of functional groups [50]. For example, the DNA molecule can be functionalized with a thiol (S–H) or a disulfide (S–S) group at the 3′ or 5′ end. Hickman et al. also verified the selective and orthogonal self-assembly of disulfide with gold and isocyanide with platinum [51]. It should be noted that there are some other strategies to attach DNA to surfaces, for example, the covalent binding of DNA oligonucleotides to a preactivated particle surface [52] and adsorption of biotinylated oligonucleotides on a particle surface coated with avidin [53, 54]. These attachment schemes have served as the fundamental base for DNA-related self-assembly of artificial nanostructures.

Construction of nanostructures using DNA self-assembly

DNA shows the potentiality to serve as a construction material in nanobiotechnology. Nature provides a complete toolbox of highly specific DNA electronic nanodevices which enables the processing of the DNA material with atomic precision and accuracy. Now a day, there has been a remarkable interest to develop concepts and approaches for self-assembled systems [55]. Although significant work continues along this direction, it has also been recognized that the exquisite molecular recognition of various natural biological materials can be used to form a complex network of potentially useful particles for a variety of magnetic, optical, electronic, and sensing applications. This approach can be considered a bottom-up approach rather than the top–down approach of conventional scaling. Regardless of its simplicity, the highly specific Watson–Crick hydrogen bonding allows convenient programming of artificial DNA receptor moieties. The PCR (polymerase chain reaction) technique is one of the major biological tools to amplify DNA sequences. DNA has great mechanical rigidity of short double helices, So that they can act effectively like a rigid rod spacer between two tethered functional molecular components on both ends. Furthermore, DNA displays a relatively high physicochemical stability [55].

Self-assembly using artificial DNA

While a variety of approaches to DNA-based supramolecular chemistry, the strategy of replacing DNA natural bases by another base that possess distinct shape, size, or function has allowed the modification of DNA in a highly specific and site selective manner [56, 57]. A good example is the replacement of the natural bases by artificial nucleosides or nucleoside mimics [58]. Yet, this approach is restricted to molecules with shapes and sizes that are equal to normal bases to ensure that the DNA modifications occur highly specifically and site selectively [58]. Lately, a new generation of such nucleoside mimics has also reported in which the hydrogen bonding interactions were replaced by metal-mediated base pairing [59, 60]. The advantage of this modification strategy is that it allows the metal ions to be replaced in the interior of the DNA duplex. This represents an important structural prerequisite for the development of new molecular devices based on interacting metal centers. Metal ions like Cu^{2+}, Pd^{2+}, and Ag^{+}, have also been successfully incorporated as artificial DNA bases into oligonucleotides by different groups[61]. Introduction of such metal-induced base pairs into DNA would not only affect the assembly–disassembly processes and the structure of DNA double strands but also provide a variety of metal-based functions upon DNA. A significant consequence of the insertion of just one artificial metal-ion-mediated base pair is that the thermal stability of the modified DNA duplex is strongly enhanced relative to one with normal hydrogen-bond interactions. Tanaka et al. [59], showed that substitution of hydrogen-bond base pairing present in natural DNA by metal-mediated base pairing, with the subsequent arrangement of these metallo-base pairs into a direct stacked contact, could lead to

"metallo-DNA" in which metal ions are lined up along the helical axis in a controlled manner. Rapidly, they have effectively arranged Cu^{2+} ions into a magnetic chain using the artificial DNA [62].

DNA tiles self-assemble into lattices

Fu and Seeman [9] initiated a family of DNA tiles known collectively as DX tiles that consisted of two parallel DNA helices linked by two immobile Holliday junctions. These tiles formed large 2D lattices, as could be viewed by AFM. DNA lattice is composed of a group of DNA tiles that are assembled together via hybridization of their pads. Generally the strands composing the DNA tiles are planned to have a melting temperature above those of the pads, ensuring that when the component DNA molecules are combined together in solution, first the DNA tiles assemble, afterward the solution is further cooled, and tiles bind each other through hybridization of their pads. Lots of computer software systems have been developed for the design of the DNA sequences composing DNA tiles, and for optimizing their stability [63]. For programming the tiling assembly, the pads of tiles is designed so that tiles assemble together as intended. Appropriate designs ensure that only the adjacent pads of neighboring tiles are complementary, so only those pads hybridize together. Consequently, other DNA tiles were developed for providing the more complex strand topology and interconnections, including a family of DNA tiles known as TX tiles [63], composed of three DNA helices linked by four crossover junctions. Both the DX tiles and the TX tiles are rectangular in shape, where two opposing edges of the tile have pads consisting of ssDNA sticky ends. Besides, TX tiles have topological properties which allows for strands to propagate in useful ways to form tile lattices. Further DNA tiles known as cross tiles are shaped roughly square, and have pads on all four sides, allowing for binding of the tile directly with neighbors in all four directions in the lattice plane (Fig. 3).

Finite-size, fully addressable DNA tile lattices

DNA has excellent intrinsic characteristics, which include molecular-scale structuring properties, self-organization, molecular recognition, and programmability, make it an attractive nanoscale building material. Their useful applications have been limited by a lack of finite-size control and unique addressability in the assembled objects [64]. A finite-sized assembly has been prototyped with cleverly designed RNA puzzle pieces, and has been shown to form objects with the potential for symmetric addressability [65]. Nevertheless their use for the display of any arbitrary 2D pattern has not yet been demonstrated. In 2006

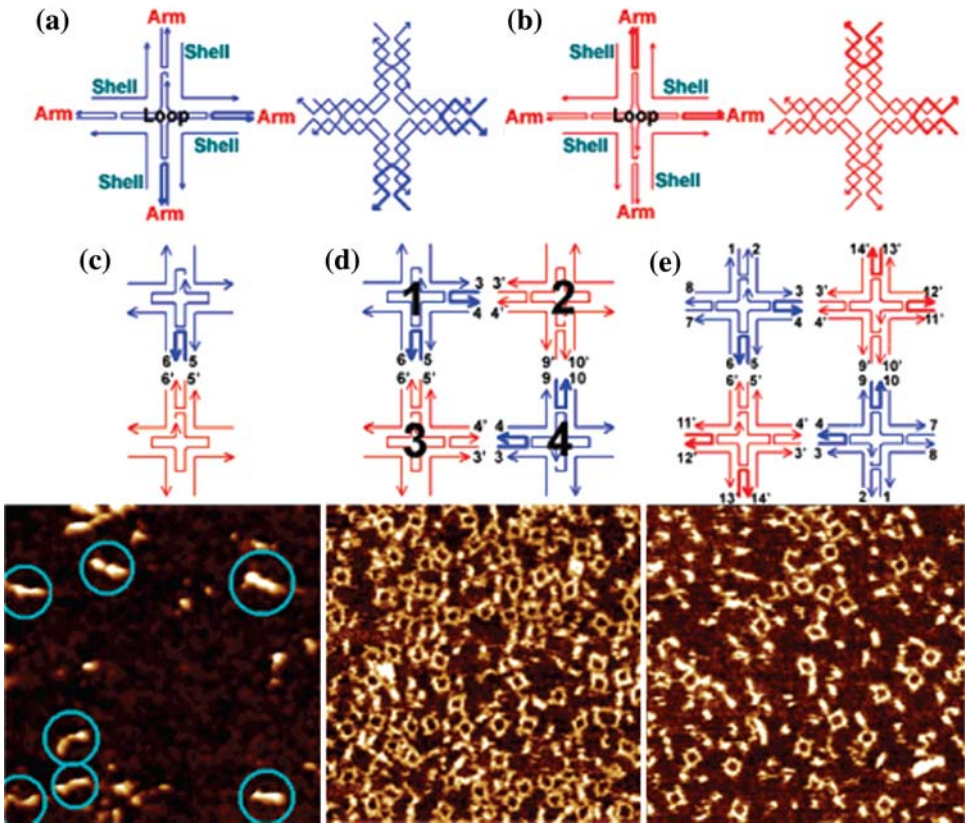

Fig. 3 Schematic drawings and AFM images of tiles and NAs (without dsDNA bridges): **a** A-tile, **b** B-tile, **c** 1 × 2 NA, **d** and **e** 2 × 2 NA without and with outer sticky-end arm strands, respectively. Scans are (**c**) 250 × 250 nm and (**d** and **e**) 500 × 500 nm (Permission from American Chemical Society)

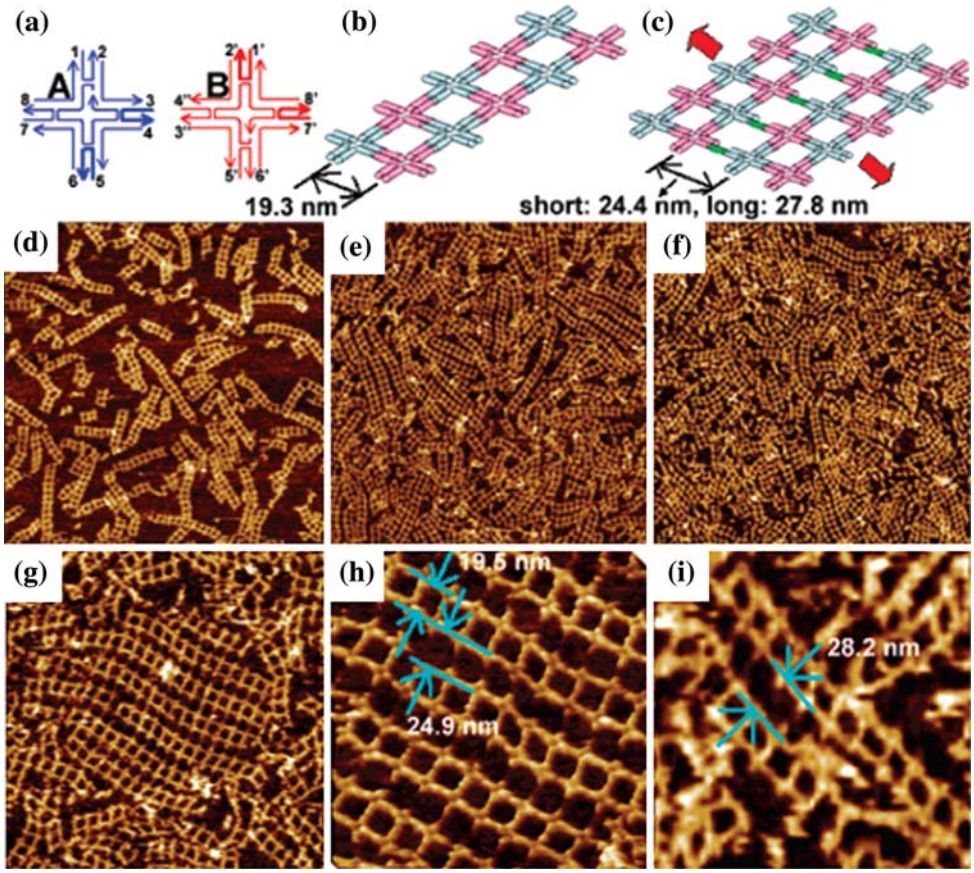

Fig. 4 **a** Drawings of A and B cross tiles, **b** cartoon of a nanotrack (NT), **c** NT with dsDNA bridges. *Red arrows* indicate growth-directions due to the possibility of assembling additional dsDNA bridges. AFM images are given (1 × 1 nm scans) for **d** NT without bridges, **e** NT with short-bridges, and **f** NT with long-bridges; **g** and **h** high-resolution AFM images of NTs with short-bridges (500 × 500 nm and 200 × 200 nm scans); **i** AFM image of NTs with long-bridges (200 × 200 nm scan). Observed dimensions are in good agreement with designed structures (Permission from American Chemical Society)

Park et al., have reported the prototype fabrication of size controllable, fully addressable, and precisely programmable DNA-based nanoarrays (NAs) consisting of cross-shaped tiles by using a novel stepwise hierarchical assembly technique [64]. Besides they have also implemented the construction of fully addressable, finite-size "N (row) > M (column)" NAs from DNA tiles with four arms, each of which contains a Holliday junction-like crossover [15, 66]. These DNA tiles are referred here as "cross tiles" (Fig. 4).

Stepwise self-assembly of DNA tile lattices aided by dsDNA bridges

In 2007 Park et al. have demonstrated the dsDNA nano bridges activities in joining of preformed DNA lattice pieces in controlled ways. DNA superstructures composed of 2 × 2 NAs and dsDNA bridges. Their two distinct self-assembled DNA superstructures are implemented and observed by AFM. (i) finite-size lattice formed from 2 × 2 nanoarrays (NAs) [64] plus dsDNA bridges (ii) extended lattices formed from nanotracks [66] (NTs) plus dsDNA bridges [67].

Reliable algorithmic self-assembly of DNA tiles

Bottom-up fabrication of nanoscale structures relies on chemical processes to direct the self-assembly. In 2007 Kenichi et al., have reported the reliable algorithmic self-assembly within a programmable nucleated finite-width ribbon which has the superior ability to control the thermodynamics and kinetics of multistage self-assembly processes in one-pot reactions. In their experiment crystals have been grown to ~300 nm long, containing ~300 tiles with an initial assembly error rate of ~1.4% per tile. To achieve this result, they have modified the design of DNA tiles to improve the tile formation yield and demonstrated that boundary tiles can prevent aggregation and merging of growing crystals [68].

Peng et al., reported the construction of DNA lattices using a flexible, single-stranded DNA motif, which is substantially simpler than the current practice of using multi-stranded rigid tiles. During lattice formation, the motif configures itself into a tile-like geometry, and motif–motif interactions result in emergent rigidity along the extended growth direction of the lattice. Significantly, this flexible motif allows us to program the tube circumference as an emergent property which is collectively defined by the modular interactions between the motifs. In the resulting

framework, a simple pairing of modular domains in the single motif may results in the self-assembly of mono disperse DNA tubes with designed circumferences [69].

The ribbon and tube systems constructed to find their applications ranging from biophysics to electronics and to nanotechnology. In biophysics, the programmable dimensions of the ribbons and tubes and, hence, their programmable physical properties, e.g., persistence length, make them attractive synthetic model systems. Douglas et al. demonstrated the design and assembly of nanostructures approximating six shapes—monolith, square nut, railed bridge, genie bottle, stacked cross, and slotted cross—with precisely controlled dimensions ranging from 10 to 100 nm. This strategy for self-assembling custom three-dimensional shapes will provide a general route to the manufacture of sophisticated devices bearing features on the nanometer scale [70].

Self-assembled DNA nanostructures reported mostly are one- or two-dimensional [71, 72]. Examples of three-dimensional DNA structures include cubes [73], truncated octahedral [50], octahedral [74], and tetrahedral [75, 76] which are all comprised of many different DNA strands with unique sequences. When aiming for large structures, the need to synthesize large numbers (hundreds) of unique DNA strands poses a challenging design problem [72, 77]. In 2008 Yu He and coworkers demonstrate the design of basic DNA building units in such a way that many copies of identical units assemble into larger three-dimensional structures. They tested this hypothesis by assembling a DNA tetrahedron from four three-point-star tiles. Each tile sits at a vertex and its branches each associate with a branch from another tile to form the edges of the tetrahedron. The assembled tiles at the four vertices retain the threefold rotational symmetry of the free, individual star tiles, but are no longer planar. In fact, they are significantly bent and thus need to be quite flexible. To provide this flexibility, the loop length is designed to be five bases long. This ensures that the DNA stars will associate with each other under hybridization conditions to form highly flexible assemblies, which allows the free sticky-ends in the assemblies to meet and associate with each other to yield closed structures (without any free sticky-ends). The size of the closed structures is concentration-dependent [78]. By controlling the flexibility and concentration of the tiles, the one-pot assembly yields tetrahedra, dodecahedra, or buckyballs that are tens of nanometers in size and comprised of 4, 20, or 60 individual tiles, respectively. This assembly strategy can be adapted to allow the fabrication of a range of relatively complex three-dimensional structures.

The hierarchical assembly strategy is evolving for functional surface mosaics [64]. DNA tiles of almost any shape can be designed; functional molecules can be placed in precise locations on a tile; and surface templating dictated by tile-template shape and size can allow specific surface placement. Technologies that could benefit from this hierarchical ability include multiplexed heterogeneous catalysis, 'lab-on-a-chip' applications, molecular electronics, solar cells, various optical and logic devices, and numerous biomedical applications with templated sites governing cell, bacteria, and biomolecule functions [79]. In short, the unique opportunities offered by DNA's intrinsic material properties, combined with current lithographic capabilities, provide new and exciting opportunities for scientific inquiry and technological advances.

Reconfigurable, braced, 3D DNA nanostructures

Goodman et al. demonstrate the operation of reconfigurable DNA tetrahedra whose shapes change precisely and reversibly in response to specific molecular signals. Shape changes are confirmed by gel electrophoresis and by bulk and single-molecule Forster resonance energy transfer measurements. DNA tetrahedral are natural building blocks for three-dimensional construction [80] they may be synthesized rapidly with high yield of a single stereoisomer, and their triangulated architecture conveys structural stability. The introduction of shape-hanging structural modules opens new avenues for the manipulation of matter on the nanometer scale [75].

Use of computational assembly of patterned 2D DNA lattices

A two-dimensional computational assembly is one of the interesting methods. Remember that computer scientists have in the 1970's shown that any computable 2D pattern can also be so assembled. 2D DNA lattice is found in MUX designs for address memory, and so this patterning might have major applications for patterning molecular electronic circuits. In the context of molecular manipulation on DNA molecule, there are two main types: simple hybridization and enzymatic treatment. Hybridization is the basic form of DNA activity, while enzymatic treatment provides ways for transaction among different DNA forms [1].

Zhang et al. noted the use of combinatorial cellular automata in designing any tiling shapes. Moreover, the natural affinity of DNA to bind with proteins, some types of small molecules, even metal atoms, makes it possible that assembled DNA can work as an inherent or transient matrix for novel computing devices [81].

3D DNA lattices to scaffolding of proteins into 3D arrays

A three-dimensional DNA lattice is used for scaffolding of proteins into regular 3D arrays. It has been predictable that at least one half of all natural proteins cannot be readily crystallized, and have unknown structure, and determining these structures would have a major impact in the biological sciences. Most probably, a 3D DNA lattice can be assembled with sufficient regularity and regular interstices which captures the given protein within each of the lattice's interstices, allowing it to be in a fixed orientation at each of its regularly spaced locations in 3D [1]. This would allow the protein to be arranged in 3D in a regular way to allow for X-ray crystallography studies of its structure. This visionary idea is attributable to Seeman. Hitherto there has been only limited success in assembling 3D DNA lattices, and they do not yet have the degree of regularity which is required for the envisioned X-ray crystallography studies. However, given the successes up to now for 2D DNA lattices, this seems eventually achievable [82].

Self-assembly of aptamer-circular DNA nanostructures

Nucleic acids specifically bind to proteins (aptamers) which can provide the affinity interactions for the self-organization of the hybrid nanostructures [33]. For example, two aptamers that bind to two different domains on thrombin, and this was used to self-assemble 1D aptamer–thrombin nanowires. Predesigned aptamer–oligonucleotide macro-monomers act as ''glues'' for the synthesis of linear or branched protein (thrombin) nanostructures.

In 2009 Wang et al. demonstrated cross linking of circular DNAs by means of bridging cocaine–aptamer subunits leads to supramolecular complexes, which form nanowires. Cocaine induced self-assembly of nanowires consisting of circular DNA and aptamer subunits as glue. In the previous reports [36, 83], which used nucleic acid hybridization as driving force for the formation of the nanowires. In this report, they applied the affinity interactions of a low-molecular weight substrate (cocaine) with its aptamer subunits to self-assemble supramolecular DNA nanowires. Also they proved the nanowires provide a scaffold for the activation of an enzyme cascade [84].

Molecular transport devices from self-assembled DNA

The development of an efficient catalytic DNA fuel delivery mechanism [85] should enable the rational design of a completely artificial DNA walker that locomotes autonomously, allowing detailed programming of a motor protein mimic. Jong et al. have showed a synthetic molecular walker that mimics the bipedal gait of kinesin [47]. Recently, there has been a progressive research works that can be done at the molecular scale which would be significantly aided by this technology. For example, many molecular tasks may need the transport of molecules. The cell uses protein motors fueled by ATP to do this. Whereas a number of motors composed of DNA nanostructures have been demonstrated, they did not operate autonomously, and instead require some sort of externally mediated changes on each work-cycle of the motor [47]. Peng et al. [86], first experimentally verified the autonomously operating device composed of DNA providing transport.

DNA origami

DNA origami, in which a long single strand of DNA is folded into a shape using shorter 'staple strands' [72] which can display 6-nm-resolution patterns of binding sites, in principle allowing complex arrangements of carbon nanotubes, silicon nanowires, or quantum dots. However, DNA origami is synthesized in solution and uncontrolled deposition results in random arrangements; this makes it difficult to measure the properties of attached nanodevices or to integrate them with conventionally fabricated microcircuitry.

In 2005, Rothemund intensely explained the developed method for folding long single strands of DNA into arbitrary two-dimensional shapes using a raster fill technique 'scaffolded DNA origami' [72] (Described briefly in reference Paul W.K. Rothemund, Design of DNA origami, 2005, IEEE).

Paul Rothemund, Gregory Wallraff and colleagues at the California Institute of Technology and the IBM Almaden Research Center describe the shape-dependent templating of DNA origami pieces onto lithographed solid supports [87]. They first produce hollow triangular DNA origami [72] tiles, with dimensions of $\sim$120 nm, in electrolyte solutions. The tiles then 'find' complementary sites in templates that have been lithographically etched on a surface (silicon oxide or diamond-like carbon in this work), to which they can bind with high selectivity and the correct orientation [79]. Deng and Mao [88] established another use of DNA in electronics by using lattice to act as a lithographic mask. After deposition of the DNA lattice onto mica, metal evaporation, and then removal of the DNA mask, gold islands might be observed on the mica surface displaying the negative of the DNA footprint.

Applications of DNA-based nanofabrication

The growth of DNA nanotechnology has led to a growing list of possible applications in materials science. DNA

nanostructures have been considered for many uses including nano mechanical devices [11, 86], computing systems [18, 89], and programmable/autonomous molecular machines [90, 91]. Nanoelectronics are being notable as another area where scientists are developing DNA-based solutions to current challenges. DNA is used to direct the assembly of a carbon-nanotube field-effect transistor [92].

Conclusions

We have focused the methods for DNA self-assembling patterns within the molecular fabric of DNA lattices. Many of these self-assembly processes are programmable and computational-based one which seems that the interdisciplinary techniques would be essential to other emerging subfields of nanoscience and biomolecular computation. Also DNA self-assembly has been design constraints and fabrication defects that must be handled by a system or architecture. Systems that overcome these challenges will benefit from the density and synthesis scale of self-assembly.

Acknowledgement This work was supported by Kyungwon University Research Fund in 2009.

References

1. Eshaghian-Wilner M (ed) (2009) Inspired and nanoscale integrated computing. Wiley, New York
2. LaBean TH, Winfree E, Reif JH (1999) Discrete Math Theoret Comput Sci 54:123
3. Jonoska N, Rozenberg G (eds) (2006) Nanotechnology: science and computation. Springer, Berlin
4. Seeman NC (2004) Sci Am 290:64
5. Seeman NC (1982) J Theor Biol 99:237
6. Kallenbach NR, Ma RI, Seeman NC (1983) Nature 305:829
7. Seeman NC, Wang H, Yang X, Liu F, Mao C, Sun W, Wenzler L, Shen Z, Sha R, Yan H, Wong MH, Ardyen PS, Liu B, Qiu H, Li X, Qi J, Du SM, Zhang Y, Mueller JE, Fu TJ, Wang Y, Chen J (1998) Nanotechnology 9:257
8. Mao C, Sun W, Seeman NC (1999) J Am Chem Soc 121:5437
9. Fu TJ, Seeman NC (1993) Biochemistry 32:3211
10. Sha R, Liu F, Millar DP, Seeman NC (2000) Chem Biol 7:743
11. Mao C, Sun W, Shen Z, Seeman NC (1999) Nature 397:144
12. Liu F, Sha R, Seeman NC (1999) J Am Chem Soc 121:917
13. Seeman NC (2001) Nano Lett 1:22
14. Zhang X, Yan H, Shen Z, Seeman NC (2002) J Am Chem Soc 124:12940
15. Yan H, Park SH, Finkelstein G, Reif JH, LaBean TH (2003) Science 301:1882
16. Liao S, Seeman NC (2004) Science 306:2072
17. Yang X, Wenzler LA, Qi J, Li X, Seeman NC (1998) J Am Chem Soc 120(38):9779
18. Mao C, LaBean TH, Reif JH, Seeman NC (2000) Nature 407:493
19. Ding BQ, Sha RJ, Seeman NC (2004) J Am Chem Soc 126:10230
20. Liu D, Wang M, Deng Z, Walulu R, Mao C (2004) J Am Chem Soc 126:2324
21. Reishus D, Shaw B, Brun Y, Chelyapov N, Adleman L (2005) J Am Chem Soc 127:17590
22. Ke Y, Liu Y, Zhang J, Yan H (2006) J Am Chem Soc 128:4414
23. Wei B, Mi Y (2005) Biomacromolecules 6:2528
24. Mathieu F, Liao S, Kopatsch J, Wang T, Mao C, Seeman NC (2005) Nano Lett 5:661
25. Li H, Carter JD, LaBean TH (2009) Mater Today 12:24
26. Sharma J, Chhabra R, Cheng A, Brownell J, Liu Y, Yan H (2009) Science 323:112
27. LaBean TH (2009) ACS national meeting, Salt Lake City, Utah
28. Simmel FC (2008) Angew Chem Int Ed 47:5884
29. Le JD, Pinto Y, Seeman NC, Forsyth KM, Taton TA, Kiehl RA (2004) Nano Lett 4:2343
30. Li H, Park SH, Reif JH, LaBean TH, Yan H (2004) J Am Chem Soc 126:418
31. Rinker S, Ke Y, Liu Y, Chhabra R, Yan H (2008) Nat Nanotechnol 3:418
32. Fruk L, Müller J, Weber G, Narváez A, Domínguez E, Niemeyer CM (2007) Chem Eur J 13:5223
33. Weizmann Y, Braunschweig AB, Wilner OI, Cheglakov Z, Willner IA (2008) Proc Natl Acad Sci 105:5289
34. Diehl MR, Zhang K, Lee HJ, Tirrell DA (2006) Science 311:1468
35. Niemeyer CM, Koehler J, Wuerdemann C (2002) ChemBioChem 3:242
36. Wilner OI, Weizmann Y, Gill R, Lioubashevski O, Freeman R, Willner I (2009) Nat Nanotechnol 4:249
37. Abbaci A, Haliyo DS, Regnier S (2008) Second international conference on quantum, nano and micro technologies, Sainte Luce, Martinique, February
38. Held GA, Grinstein G, Tu Y (2003) Proc Natl Acad Sci 100:7575
39. Chen YA, Chou CC, Lu X, Slate EH, Peck K, Xu W, Voit EO, Almeida JS (2006) BMC Bioinform 7:101
40. Peterlinz KA, Georgiadis RM (1997) J Am Chem Soc 119:3401
41. Gao Y, Wolf LK, Georgiadis RM (2006) Nucleic Acids Res 34:3370
42. Carlon E, Heim T (2006) Physica A 362:433
43. Mirkin CA, Letsinger RL, Mucic RC, Storhoff JJ (1996) Nature 382:607
44. Strother T, Cai W, Zhao X, Hamers RJ, Smith LM (2000) J Am Chem Soc 122:1205
45. Sieval AB, Demirel AL, Nissink JWM, Linford MR, Maas JH, de Jeu WH, Zuilhof H, Sudholter ERJ (1998) Langmuir 14:1759
46. Linford MR, Fenter P, Eisenberger PM, Chidsey CED (1995) J Am Chem Soc 117:3145
47. Turberfield AJ, Mitchell J, Yurke B, Mills APJ, Blakey M, Simmel F (2003) Phys Rev Lett 90:102
48. Nuzzo RG, Allara DL (1983) J Am Chem Soc 105:4481
49. Bain CD, Whitesides GM (1989) Angew Chem Int Ed 28:506
50. Zhang YW, Seeman NC (1994) J Am Chem Soc 116:1661
51. Hickman JJ, Laibinis PE, Auerbach DI, Zou C, Gardner TJ, Whitesides GM, Wrighton MS (1992) Langmuir 8:357
52. Pathak S, Choi SK, Arnheim N, Thompson ME (2001) J Am Chem Soc 123:4103
53. Alivisatos AP, Johnsson KP, Peng X, Wilson TE, Loweth CJ, Bruchez MP, Schultz PG (1996) Nature 382:609
54. Niemeyer CM, Burger W, Peplies J (1998) Angew Chem Int Ed 37:2265
55. Sun Y, Kiang CH (2005) Nanobiotechnology 2:224
56. Beaucage SL (ed) (2007) Current protocols in nucleic acid chemistry. Wiley, New York
57. Carell T, Behrens C, Gierlich J (2003) Biomol Chem 1:2221
58. Kool ET (2002) Acc Chem Res 35:936
59. Tanaka K, Shionoya M (1999) J Org Chem 64:5002
60. Atwell S, Meggers E, Spraggon G, Schultz PG (2001) J Am Chem Soc 123:12364
61. Wagenknecht HA (2003) Angew Chem Int Ed 42:3204

62. Tanaka K, Tengeiji A, Kato T, Toyama N, Shionoya M (2003) Science 299:1212
63. Landweber LF, Baum EB (eds) (1999) DNA based computers II. American Mathematical Society, Rhode Island
64. Park SH, Pistol C, Ahn SJ, Reif JH, Lebeck AR, Dwyer C, LaBean TH (2006) Angew Chem Int Ed 45:735
65. Chworos A, Severcan I, Koyfman A, Weinkam P, Oroudjev E, Hansma H, Jaeger L (2004) Science 6:2068
66. Park SH, Yin P, Liu Y, Reif JH, LaBean TH, Yan H (2005) Nano Lett 5:729
67. Park SH, Finkelstein G, LaBean TH (2008) J Am Chem Soc 130:40
68. Fujibayashi K, Hariadi R, Park SH, Winfree E, Murata S (2008) Nano Lett 8:1791
69. Yin P, Hariadi RF, Sahu S, Choi HMT, Park SH, LaBean TH, Reif JH (2008) Science 321:824
70. Douglas SM, Dietzl H, Lied T, Högberg B, William FG, Shih M (2009) Nature 459:414
71. Winfree E, Liu FR, Wenzler LA, Seeman NC (1998) Nature 394:539
72. Rothemund PWK (2006) Nature 440:297
73. Chen JH, Seeman NC (1991) Nature 350:631
74. Shih WM, Quispe JD, Joyce GF (2004) Nature 427:618
75. Goodman RP, Schaap IAT, Tardin CF, Erben C, Berry RM, Schmidt CF, Turberfield AJ (2005) Science 310:1661
76. Goodman RP, Berry RM, Turberfield AJ (2004) Chem Commun 1372
77. Douglas SM, Chou JJ, Shih WM (2007) Proc Natl Acad Sci 104:6644
78. He Y, Ye T, Su M, Zhang C, Ribbe AE, Jiang W, Mao C (2007) Nature 452:198
79. Grainger DW (2009) Nat Nanotechnol 4:543
80. Goodman RP, Heilemann M, Doose SR, Erben CM, Kapanidis AN, Turberfield AJ (2008) Nat Nanotechnol 3:93
81. Zhang Z, Fan C, He L (2005) Curr Nanosci 1:89
82. LaBean TH, Yan H, Kopatsch J, Liu F, Winfree E, Reif JH, Seeman NC (2000) J Am Chem Soc 122:1848
83. Wilner OI, Shimron S, Weizmann Y, Wang ZG, Willner I (2009) Nano Lett 9:2040
84. Wang ZG, Wilner OI, Willner I (2009) Nano Lett 9:4098
85. Shin JS, Niles Pierce A (2004) J Am Chem Soc 126:10834
86. Yin P, Yan H, Daniel XG, Turberfield AJ, Reif JH (2004) Angew Chem Int Ed 43:4906
87. Kershner RJ, Bozano LD, Micheel CM, Hung AM, Fornof AR, Cha JN, Rettner CT, Bersani M, Frommer J, Rothemund PWK, Wallraff GM (2009) Nat Nanotechnol 4:557
88. Deng Z, Mao C (2004) Angew Chem Int Ed 43:4068
89. Benenson Y, Elizur TP, Adar R, Keinan E, Livneh Z, Shapiro E (2001) Nature 414:430
90. Green SJ, Lubrich D, Turberfield AJ (2006) J Biophys 91:2966
91. Venkataraman S, Dirks RM, Rothemund PWK, Winfree E, Pierce NA (2007) Nat Nanotechnol 2:490
92. Keren K, Berman RS, Buchstab E, Sivan U, Braun E (2003) Science 302:1380