

is the large dynamic movement (up to ~200-nm expansion in one direction or approximately fivefold aspect ratio change) brought about by a small set of triggers (as few as five DNA strands). In the largest relay array, 160 reconfigurable units communicate their structural information through more than 300 flexible joints. Interestingly, squarelike DNA antijunctions that are unstable by themselves exist in relay arrays as bridges between rhombic units of different conformations, which are elegant examples of stabilized structure-switching intermediates. In addition, the information relay is generalizable in 3D; rolling up a sheet of relay array yields a DNA tube that can change its diameter and length simultaneously.

Although a few limitations of the system remain to be resolved (such as the slow transformation kinetics and the requirement of denaturing conditions), the reconfigurable DNA arrays are extremely exciting because they present enormous possibilities. For DNA nanotechnology specialists, the relay arrays provide a platform with which to model the cooperative dynamics of DNA junctions. Integrating the relay mechanism into other DNA nanostructures may generate biologically relevant motions, such as the rotary and swinging motions of flagella and cilia. For developing applications, one could place guest molecules (for example, fluorophores, nanowires, or enzymes) on the DNA arrays (9) and thus convert the mechanical movement into optical, electrical, or chemical signals. Such constructs may be useful for sensing biomolecules and studying their collective dynamic behaviors. Last, with the rapid development of DNA nanostructure-based membrane engineering methods, it may be possible to interface the dynamic DNA arrays with artificial or biological membranes. One could envisage making expandable DNA nanopores across lipid bilayers (10), constricting liposomes templated by DNA tubes (11), and clustering cell surface receptors to elicit functional responses (12). ■

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LITHOGRAPHY

Photolithography based on nanocrystals

Surface chemistry of all-inorganic nanomaterials enables three-dimensional patterning

By **Marinella Striccoli**

Colloidal chemistry allows the fabrication of metal, semiconductor, oxide, and magnetic nanocrystals (NCs) with well-controlled sizes and shapes, as well as of heterostructures with exotic shapes and composition (1). Such NCs are promising materials in several technological fields. For example, the high-purity emission color of semiconductor NCs has been applied in optical displays (2), and their broadband absorption has been exploited in innovative solar cells (3). Other applications include field-effect transistors, light-emitting diodes, and sensors (4). However, for the fabrication of advanced electronic devices in a parallel and scalable fashion for industrial production, NCs must be integrated into structures to bridge the gap between the

nano- and mesoscopic regimes (5). Thus, the organization of NCs in morphologically controlled patterns and processable systems is of paramount importance. On page 385 of this issue, Wang *et al.* (6) present a pioneering and straightforward approach for the patterning of functional inorganic NCs on substrates with optical lithography. This advance could add—literally—a multilayer dimension to the development of NC-based devices.

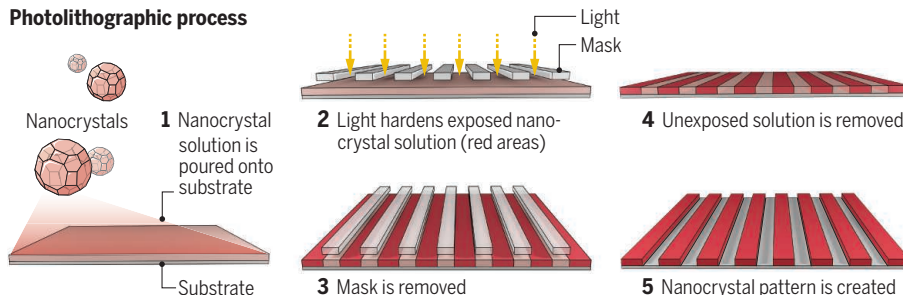
The manufacturing of consumer electronics requires the fabrication of integrated circuits (ICs). For this purpose, metals, semiconducting, and oxide materials are typically patterned by means of ultraviolet (UV) lithography, a photographic process. A light-sensitive material (a photoresist) is exposed and developed to form three-dimensional (3D) structures or patterns on a substrate. The photoresist is mainly composed of photosensitizers, polymers, solvents, and additives and can be positive or negative, depending on whether it became soluble or insoluble to the developer, respectively, after exposure to light.

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Direct nanocrystal patterning

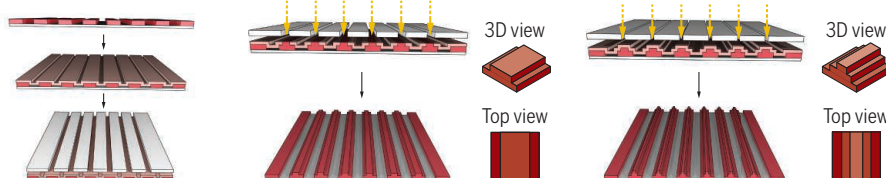
Optical patterning of nanocrystals can add a third dimension to traditional microlithography. Wang *et al.* modify the surface chemistry of nanocrystals with photoactive inorganic ligands to fabricate resists from solution that can be easily microstructured.

Photolithographic process



Layer production

Multiple layers can be patterned sequentially, obtaining all-inorganic 3D structures with vertical resolution of a few nanometers.



A conventional photoresist usually does not possess any inherent functionality. It is used only to mask the active material and, in a subsequent subtractive etching process, pattern it in defined geometries. The fabrication even of a simple IC element requires several sequential steps, based on well-assessed protocols, and multilayered patterning can be needed for completing the whole process. Each step has a non-negligible cost because the processes require high-vacuum and high-temperature conditions, so limiting the number of steps can lower the device production cost. However, with respect to other techniques such as electron-beam lithography or inkjet printing, UV lithography permits the simultaneous fabrication of millions of elements at a resolution of few tens of nanometers. For these reasons, it has been widely adopted for the production of IC circuits, transistors, and optoelectronic devices.

A number of approaches have been developed for patterning NC-based materials (7). For example, NCs were added to the photoresist formulation with a common solvent. Such a route can effectively integrate specific functionalities in the resist, essentially retaining its resolution (8). However, the organic components of the resist interfered with the optical and electrical properties of the NCs and inhibited the conductivity of the patterned materials.

The methodology proposed by Wang *et al.* is based on a peculiar characteristic of the colloidal NCs, the presence of a capping layer formed by surfactant molecules. The surfactant controls NC growth during the synthesis and allows their dispersion in organic solvents. More importantly, the native surfactant layer can be modified after synthesis with different ligands, including inorganic ions, molecules, and polymers. In addition, ligands can influence the optical and electronic properties of NCs and can be optimized for specific applications. In particular, short inorganic ligands facilitate the charge transport between NCs, resulting in electronic and optoelectronic devices with improved performance (9).

If the NC surface is functionalized by inorganic capping agents, which themselves act as photosensitizers, the dispersion of NCs alone can be a resist. In the work of Wang *et al.*, properly designed ionic ligands, engineered to be photoreactive, solubilize NCs as in a positive resist or render them insoluble as in a negative resist after light exposure and developing. Following this approach, entire classes of resists can be suitably designed

and produced by using NCs with diverse size and composition in solvent solution, without the addition of conventional photoresist or other organic contaminants. Such dispersions function as inks that can be deposited in thin films by spin-coating on plastic, glass, or silicon substrates and directly patterned with optical lithography, to easily fabricate complex geometries made only of NCs. Moreover, the direct optical lithography of NC-based inks requires many fewer steps with respect to conventional lithography, which should reduce processing costs.

The method has been successfully applied to metal, semiconductor, magnetic, or oxide NCs and to up-converting nanostructures, obtaining patterns with a resolution limited by the used optical mask. The different physical and chemical properties of the NCs are not altered by the photoactive inorganic ligands, so it is possible to fabricate luminescent patterns, magnetic stripes, or transparent electrodes with optimal conductive properties and micrometer structuring without losing the size-dependent properties of the NCs. Because of the high NC optical absorption, the thickness of the NC layer, impressed in a single exposure step, is limited to few tens to hundreds of nanometers. However, multiple layers of the same or different materials can be deposited and patterned sequentially, obtaining 3D all-inorganic structures with ~10-nm accuracy along the vertical direction (6).

The innovative approach of Wang *et al.* offers a valuable toolbox with which to overcome the very expensive techniques of traditional microfabrication to produce integrated high-performance NC device elements via simple, solution-based processes at room temperature over a large area. One can even imagine the patterning of inks formed of NCs with diverse composition—and hence, functions—for the fabrication of complex multifunctional structures not achievable in conventional monolithic materials. ■

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GENOME BIOLOGY

The genome— seeing it clearly now

Genome architecture
is revealed with
electron tomography

By Daniel R. Larson and Tom Misteli

It is a curious fact that in many fields of science, central questions that one might assume to have been answered decades ago remain perennially unresolved. In genome biology, one such cornerstone problem has been how DNA is organized in an intact cell nucleus. This conundrum is an important and intriguing one because the human genome is over 2 m in length and yet it is packed into a cellular compartment that is merely about 10 μm in diameter. On page 370 of this issue, Ou *et al.* (1) now take a major step toward answering this foundational question.

We know, mostly from biochemical *in vitro* studies, that DNA forms higher-order structures in the shape of chromatin fibers, which comprise DNA wrapped around architectural histone proteins, together referred to as nucleosomes and often thought of as “beads on a string” (see the figure). Interactions between distal parts of the chromatin fiber result in higher-order folding and compaction (2). But why do we not know what this compacted chromatin polymer looks like in a cell nucleus? Most models suggest that the chromatin fiber is around 5 to 100 nm in diameter. This places chromatin in the “blind spot” of most imaging methods. These dimensions are largely below the resolution limit of light microscopy. Even super-resolution imaging, which increases the resolving power of the light microscope beneath the diffraction limit, is not sufficient to directly visualize these dimensions. Yet, existing electron microscopy (EM) techniques, which can easily resolve objects at this scale, cannot be used to unambiguously discern chromatin fibers in intact cells because native chromatin is not electron dense.

Ou *et al.* have now developed ChromEMT (chromatin electron microscopy tomog-

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“...[nanocrystals] must be integrated into structures to bridge the gap between the nano- and mesoscopic regimes.”

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