Folding Photonic Nanostructures

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An electron beam lithography and plasma etching process enables hands-free folding of functional metal-patterned dielectric structures with nanoscale dimensions.

Functional optical and electronic modules require metals, semiconductors, and dielectrics to be patterned in intricate designs, such as those required to create transistors, filters, and antennas. The nanofabrication of such devices in planar or stacked architectures is relatively straightforward, but their patterning in curved or angled geometries remains challenging.[1] While 3D nanomachining techniques exist, such as focused ion beam milling and deposition, they are serial and expensive.

When folding cardboard boxes or paper origami cutouts, we are struck by the ease with which we can transform a planar structure into a 3D structure: see Figure 1 (left). However, at the 100nm length scale—a size about a million times smaller than a traditional cardboard box—it is not possible with existing technology to make the 3D manipulations required to fold up even a cube.

To avoid relying on ion beam milling techniques and nanomanipulators, we invented a hands-free approach to folding up nanostructures using 100nm-sized panels connected by hinges. Our inspiration for this research arose from previous work in our laboratory and elsewhere on surface tension and stress-driven self-folding at the micro- and macroscale.[2,3] Although a process termed Nanostructured Origami™ had been invented previously, the word 'nano' was used to describe the length scale of the patterns rather than the panel size, which was considerably larger.[4] To our knowledge, no one had ever folded up lithographically patterned hinged panels with dimensions of 100nm or less prior to our work.

In our laboratory, the scaling of the self-folding concept for use with tiny 100nm-sized panels and hinges required considerable experimentation and innovations in the patterning techniques, types of materials, and process flows. We invented a process that uses tin as a hinge material, multiple layers of electron beam lithography, and plasma etching to release the panels and simultaneously heat the hinges to drive self-folding in vacuum. Using this process, we showed for the first time in 2009 that it was possible to fold up a 100nm-sized cubic particle from electron-beam lithographically patterned panels and hinges.[6]

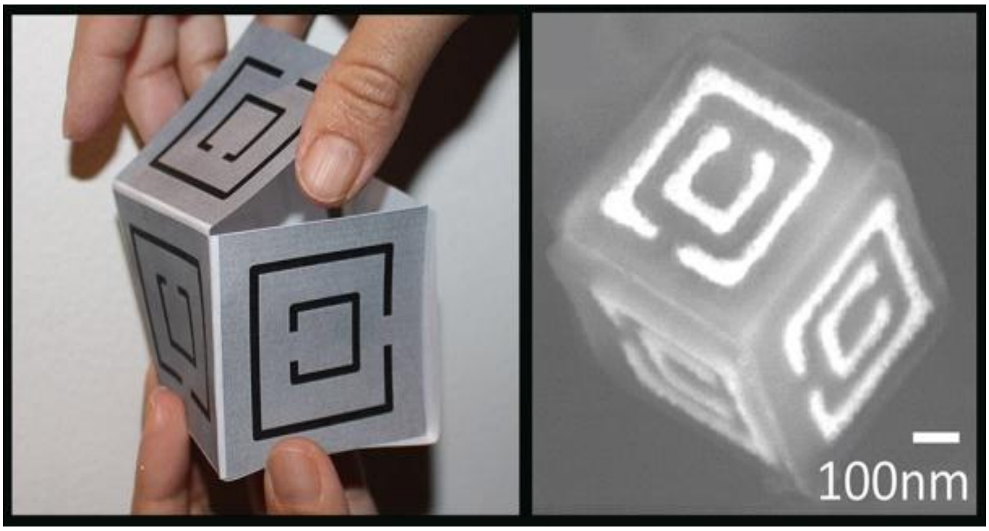

Figure 1. (left) The folding of a macroscale split-ring patterned origami cutout by hand. (right) Electron microscopy image of a self-folded cubic photonic nanostructure that was created using electron beam lithography and plasma etching. (Reprinted with permission.[5] Copyright WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim 2011.)

Our approach enables freestanding or arrayed nanostructures to be created, and we have shown that we can control the fold angle using a variety of process parameters.[5,6] To explore applications in photonics and electronics, we patterned optical modules and electronic circuits on the faces of these nanostructures. For example, we patterned metallic split-ring resonators (SRRs) on the faces of 100nm-sized dielectric squares using electron beam lithography. These squares folded up into a cubic particle wherein the metallic SRRs were positioned along three orthogonal axes in a dielectric medium: see Figure 1 (right).[5] Single-particle Fourier transform infrared reflection measurements and simulations done in collaboration with researchers at Imec suggested that such particles feature sharp quadrupolar resonances.[5] We believe that folding these photonic nanostructures could provide significant enhancements in optics, biosensing, and electronics. For example, controlling the fold angle would make it possible to elicit unique polarization-dependent responses from photonic nanostructures. Moreover, the ability to array optical elements along orthogonal axes could facilitate the creation of three-axis sensors that provide angular information, which has been demonstrated on the microscale.[7] In addition, it would be possible to aggregate these patterned particles in 3D and create isotropic and polyhedral metamaterials,[8] which would allow current loops to flow in three dimensions and offer the possibility for isotropic electromagnetic responses.

In the future, it will be necessary to expand on these proof-of-concept demonstrations in several directions. Specifically, we need to explore the use of alternate forces to fold the nanostructures, develop methods to mass-produce the structures, and pattern semiconductors, other metals, and other dielectrics. For example, researchers recently folded 100nm-scale panels using Ga^+ ion beam irradiation of metals.[9] Previously, self-folding using silicon-on-insulator substrates was shown as an attractive means to create micropolyhedra with patterned semiconducting silicon chips on their faces,[10] and such approaches need to be scaled down to the nanoscale. Our laboratory has also been investigating the use of nanoimprint lithography techniques to mass-produce self-folded nanostructures because throughput is currently limited by serial electron-beam patterning of the planar templates. Finally, similar methods also look promising in the design of simultaneously patterned and curved photonic nanostructures and a range of materials, including graphene.[11]

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