relative to the electrodes (Fig. 1b). The most prominent misalignment was an average longitudinal offset of 99 nm, with a standard deviation of 216 nm, for nanowires that were 18 μm long (so the misalignment was less than 0.6% of the nanowire length). Statistical analysis of the assembly process was integral both to achieving and communicating high self-assembly yields, and can be expected to be an essential tool for future manufacturability research.

A logical extension of the work by Freer and co-workers is to scale the process to larger areas and greater pattern complexities, involving higher densities of nanowires. For a sufficiently complex and dense design, we expect that self-assembly will become prohibitively difficult to implement, so that a more traditional lithographic process will be preferred. However, the complexity at which traditional processes will become preferred remains to be established. The present results demonstrate that the limits of self-assembly continue to be pushed back. Greater complexity will also require attention to the reliability of nanowires and other electronic components, which can be improved through engineered redundancy and parallel arrays[7], as well as by the high precision and yield demonstrated by the Nanosys researchers.

Another important factor for manufacturing devices by self-assembly of synthetic nanowires will be speed. A nanowire is isolated from solution only when it is within a given capture radius of the dielectrophoretic trap. As the nanowire suspension flows faster (or becomes more dilute), the capture probability drops. Ensuring that every electrode pair contains a nanowire could then require passing the suspension over the electrodes for an extended period of time. A potential solution may be found in careful attention to electrode design[8],as well as in the application of a pulsed electric field across the vertical axis of the channel to help direct nanowires towards the dielectrophoretic traps, improving trapping efficiency.

The detailed analysis and balancing of self-assembly forces demonstrated by Freer and co-workers[4] will play an important role in the design of future self-assembled nanowire- and nanotube-based devices. This work, and others like it, are changing the way we think about how devices can be fabricated, as bottom-up self-assembly increasingly becomes a viable complement to top-down lithography. ❐

Byron D. Gates, a Canada Research Chair, is in the Department of Chemistry and 4D LABS at Simon Fraser University, Burnaby, British Columbia V5A 1S6, Canada.
e-mail: bgates@sfu.ca

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NANOSCALE OPTICS

Plasmonics gets transformed

A high degree of control over plasmons can be achieved at the nanoscale by engineering the properties of adjacent dielectric layers.

Wenshan Cai and Mark L. Brongersma

It is hard to imagine future nanoscale photonic systems that do not involve plasmonics, a relatively new device technology that uses metals to control the flow of light at the nanoscale[1]. That is because plasmonics resolves a basic mismatch between wavelength-scale optical devices and the much smaller components of integrated electronic circuits. A wide variety of plasmonic elements have been demonstrated using metallic nanostructures, including compact sources, waveguides, modulators and detectors. These devices typically rely on surface plasmon polaritons (SPPs), which are a special type of electromagnetic wave that can travel along the surface of a patterned metallic film. This patterning, however, introduces scattering losses that cause rapid attenuation of the SPPs, limiting their range and application. Writing in *Nano Letters*, two independent teams led by Xiang Zhang at the University of California, Berkeley, and Francisco García-Vidal at the Universidad Autónoma de Madrid have proposed and numerically demonstrated the routing of SPPs by structuring the dielectric material next to the metal surface, rather than the metal itself[2,3]. This approach allows almost arbitrary control over the flow of SPPs, without the losses associated with metallic patterning.

The approach is an example of 'transformation optics'[4,5], which begins with a desired pathway for a light or plasmon wave, and works out how the properties of the material carrying the wave should vary with position to ensure that the pathway is followed. Mathematically, this involves calculating a coordinate transformation from a Euclidian (undistorted) space, in which the wave travels in a straight line, to a distorted coordinate system in which the wave travels along the desired path. This coordinate transformation is then translated to a set of spatially dependent materials parameters, including the electric permittivity ε (which sets the dielectric constant), and the magnetic permeability μ. The mathematics relies on the invariance of Maxwell's equations, which govern light waves and SPPs, under a coordinate transformation. The approach is not limited to electromagnetics, and has also been applied to static electric fields, sound waves, heat flow and even de Broglie matter waves in quantum mechanics.

Until recently, the materials parameters necessary for transformation optics (which, in general, are inhomogeneous, anisotropic and can involve unusual values of the permittivity or permeability) could not be realized in naturally occurring materials. The advent of metamaterials[6], in which parameters can be tailored with nanometre precision, addressed this need for certain applications. However, the application of transformation optics to SPPs remained impractical before the work of the García-Vidal and Zhang groups. This was because the electromagnetic fields associated with SPPs extend only a few tens of nanometres below the surfaces of the metals along which they travel. Control over the materials properties of metals on that length scale, as apparently required by transformation optics, are beyond the reach of present nanofabrication techniques.

The two papers avoid this seemingly insurmountable fabrication challenge by showing that control over the metal is not actually required. At visible and infrared frequencies, most of the energy of the SPP is contained inside a dielectric layer adjacent to the metallic layer, with dielectric penetration depths of a micrometre or more. This means that the transformation procedure can be carried out by manipulating the properties of the dielectric medium alone, while leaving the metal completely untouched. The García-Vidal and Zhang groups numerically demonstrate a beam shifter, waveguide bend, cloaking structures and Luneburg lens by manipulating only the dielectric. The ability to control SPPs by nanostructuring adjacent layers may also be used to tailor radiative decay processes, alter mode profiles, produce slow light and more.

In certain cases, the dielectric media required for transformation plasmonics need only isotropic and non-magnetic constituents, and allows for low-loss, broadband operations. These are attractive features that have been pursued for years in transformation optics[7–9]. For example, the magnetic-field component of two-dimensional SPPs lies parallel to the surface and perpendicular to the propagating direction. Therefore modifications in the magnetic permeability of the dielectric can be avoided if no spatial transformation occurs along the direction of the magnetic field. These features have been exploited in particular by the Zhang group when analysing their SPP cloaks (Fig. 1) and waveguide bends[2].

Metal-based optical components may be useful for transformation optics beyond their ability to host SPPs on their surface. Metals are unique in their ability to perform simultaneous optical and electronic functions at the nanoscale. For example, they may be used to dynamically modify the optical properties of a dielectric clamped between two metal structures, with possible application in electronically switchable transformation devices.

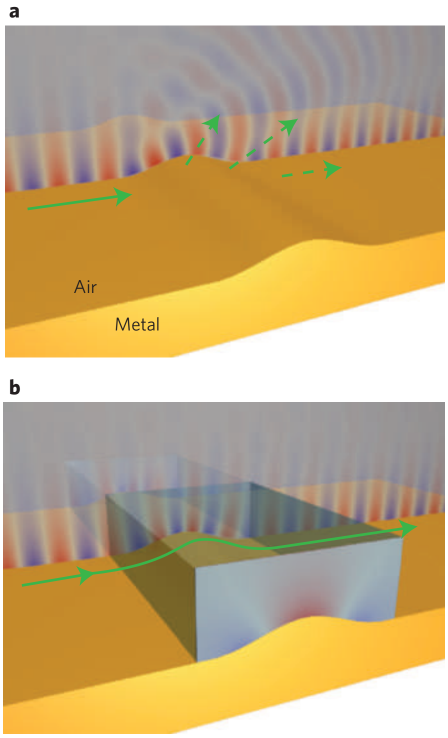

Figure 1 | Transformation plasmonics is used to reduce scattering from a surface, effecting a kind of cloak. **a**, Plasmon waves (green arrows) travelling along a metal surface experience substantial scattering losses when they encounter an obstacle such as a bump on the surface. **b**, Scattering losses are suppressed by covering the bump with a dielectric box for which the refractive index spatially varies from 0.8 (blue) to 1.4 (red). Transformation plasmonics is used to calculate how the refractive index should vary with position. In both **a** and **b**, the wave patterns show the magnetic-field components of SPPs obtained from full-wave simulations (performed by the Zhang group[2]).

We stress that the experimental realization of any transformation-based device will be technically demanding and involve the fine tuning of materials parameters with deeply subwavelength precision, except for the rare case where the transformed region consists entirely of layered films. Indeed, although the correspondence between coordinate deformation and materials parameters was realized almost five decades ago by pioneers like L. S. Dolin and E. G. Post[9], it is only by exploiting recent advances in nanofabrication and characterization tools that the field of transformation optics has flourished. The field has therefore been handed over from electromagnetic theorists to nanotechnology engineers, and the further development of transformation plasmonics relies largely on whether there really is 'plenty of room' to manipulate the properties of the micrometre-thin region of dielectrics. ❐

Wenshan Cai and Mark L. Brongersma are in the Geballe Laboratory for Advanced Materials, Stanford University, Stanford, California 94305, USA.
e-mail: brongersma@stanford.edu

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