neuronal extensions, and in particular at the extremity of projections called axons). It has been shown[8,9] that Rab11 endosomes are involved in axon growth, but the authors' analysis goes further, showing that the presence of recycling endosomes in the growth cone is directly correlated with axon extension.

The authors also used their system to test the 'tug-of-war' model for positioning organelles in neuronal protrusions called dendritic spines. This model states that a balance between stable tethering and motor-driven forces is essential to regulate the positioning of organelles. Using their system, the researchers confirmed this model and defined the precise role of particular motor proteins and anchoring factors in polarized organelle trafficking. In summary, van Bergeijk and colleagues have designed a powerful tool that, with its high spatio-temporal resolution, is a spectacular example of the ability of optogenetics to alter processes in real time in chosen subcellular areas.

Technological revolutions have often provided the tools with which to analyse cellular processes from a different point of view. Examples include the advent of RNA interference, super-resolution fluorescent imaging, and electron microscopy and its subsequent improvements, all of which were instrumental in helping cell biologists to reimagine the cell. The next challenge is not only to improve existing tools, but also to develop additional approaches to asking new questions in a comprehensive and integrated manner.

Optogenetic strategies, including van Bergeijk and co-workers' technique, will have a major part to play here. For example, the quantitative spatio-temporal data that these techniques can generate will be of great use to fields such as systems biology and theoretical modelling. The study of cell biology at the tissue or whole-organism level will similarly benefit from such an approach, because it will be possible to suddenly change the positions and dynamics of specific organelles in particular cell types, and then monitor induced defects. Gene editing now allows us to create modified versions of key cellular regulatory factors[10]. Combining optogenetic development with gene editing will enable us to control cell organization precisely and to question its role in cellular function. A bright future awaits cell biology. ■

Franck Perez *is at the CNRS UMR 144, Institut Curie, 75248 Paris 05, France.*
e-mail: franck.perez@curie.fr

1. Bornens, M. *Nature Rev. Mol. Cell Biol.* **9,** 874–886 (2008).
2. van Bergeijk, P., Adrian, M., Hoogenraad, C. C. & Kapitein, L. C. *Nature* **518,** 111–114 (2015).
3. Schliwa, M. & Woehlke, G. *Nature* **422,** 759–765 (2003).
4. de Forges, H., Bouissou, A. & Perez, F. *Int. J. Biochem. Cell Biol.* **44,** 266–274 (2012).
5. Gautier, A. *et al. Nature Chem. Biol.* **10,** 533–541 (2014).
6. Strickland, D. *et al. Nature Methods* **9,** 379–384 (2012).
7. Kennedy, M. J. *et al. Nature Methods* **7,** 973–975 (2010).
8. Bhuin, T. & Roy, J. K. *Cell Tissue Res.* **335,** 349–356 (2009).
9. Eva, R. *et al. J. Neurosci.* **30,** 11654–11669 (2010).
10. Hsu, P. D., Lander, E. S. & Zhang, F. *Cell* **157,** 1262–1278 (2014).

This article was published online on 7 January 2015.

DEVICE FABRICATION

Three-dimensional printed electronics

Can three-dimensional printing enable the mass customization of electronic devices? A study that exploits this method to create light-emitting diodes based on 'quantum dots' provides a step towards this goal.

JENNIFER A. LEWIS & BOK Y. AHN

The ability to rapidly print three-dimensional (3D) electronic devices would enable myriad applications, including displays, solid-state lighting, wearable electronics and biomedical devices with embedded circuitry. Writing in *Nano Letters*, Kong *et al.*[1] report an intriguing route to this goal by creating fully 3D-printed light-emitting diodes (LEDs) based on quantum dots. Quantum dots are semiconducting nanocrystals that exhibit tunable colour emission[2–4]. Using a 3D-printing method based on extruding multiple materials, the researchers patterned quantum-dot-based LEDs (QD-LEDs) on curved surfaces and integrated arrays of the diodes in 3D matrices.

3D printers transform the output files from computer-aided design tools into tangible objects using pattern-generating devices that move along multiple directions in space[4]. These devices can be light sources that harden resins or fuse powders, or nozzles that directly deposit materials. Since their introduction nearly three decades ago, 3D-printing methods have been used to build myriad objects, primarily prototypes, in a sequential, layer-by-layer fashion.

To create 3D objects of arbitrary form and specific function, a broad palette of materials and multi-material printing platforms are required. One promising approach is 3D extrusion printing[5], in which functional inks are deposited through fine cylindrical nozzles under an applied pressure at ambient conditions. Unlike 3D printers that use inkjet print heads, which are suitable only for inks with a narrow range of viscosities (about ten times that of pure water), extrusion-based printing enables materials of widely varying composition and viscosity to be patterned[6].

QD-LEDs are multilayer devices built around an active (light-emitting) layer composed of quantum dots[4]. Multiple QD-LED layer architectures have been explored with the aim of optimizing their external quantum efficiency, that is, the ratio of the number of photons emitted by the QD-LED relative to the number of electrons injected into the device when an electric field is applied between the device's outer metallic electrodes (cathode and anode layers). In the typical embodiment of a QD-LED, the active layer is sandwiched between layers of electron- and hole-transporting materials, where holes are positively charged carriers. The applied electric field causes electrons and holes to move into the active layer, where they recombine to emit photons.

Solution-based processing routes have recently emerged for patterning QD-LEDs with the aim of lowering fabrication costs[7,8]. Central to this approach is the ability to maintain highly uniform layers between dissimilar materials. To create their QD-LED devices, Kong and colleagues sequentially printed several materials (Fig. 1). First, a conductive silver ring that surrounds a transparent anode layer followed by a hole-transport layer were printed, and annealed at 200 °C (silver ring) and 150 °C (other layers). Next, the active layer was formed by printing quantum dots suspended in a solvent mixture in a drop-wise manner. As solvent evaporation ensued, recirculating fluid flow suppressed quantum-dot migration to the drop edge, yielding relatively uniform, active layers[9]. Notably, each layer was patterned using immiscible solvents to minimize interlayer mixing. Finally, a cathode layer composed of liquid metal was printed[10] and the devices were packaged in a silicone sealant.

To highlight the flexibility of their approach, the authors printed QD-LEDs in multiple formats, including green and orange-red light emitters, 2 × 2 × 2 arrays embedded in a silicone matrix, and QD-LEDs on the surface of contact lenses and other substrates of interest.

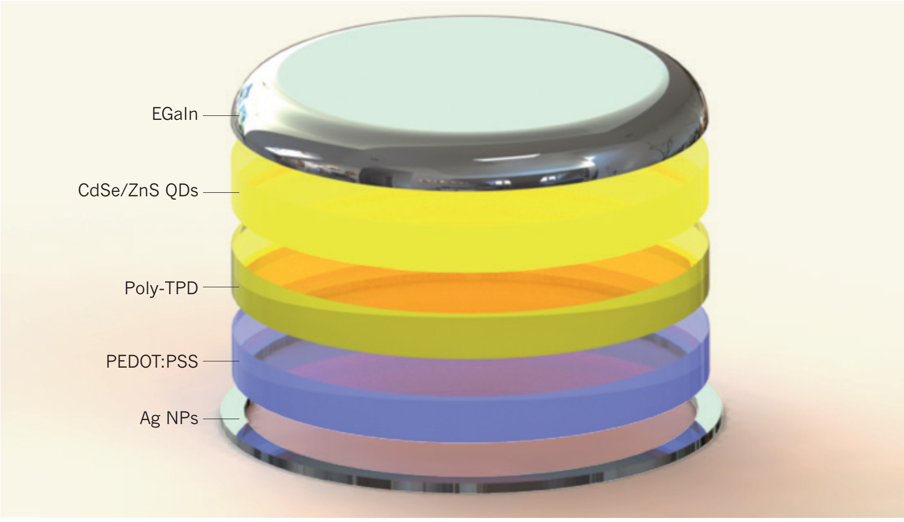

Figure 1 | Fully 3D-printed quantum-dot-based light-emitting diodes (QD-LEDs). The QD-LEDs reported by Kong and colleagues[1] consist of five layers: a conductive ring of silver nanoparticles (Ag NPs) that surrounds a transparent anode layer composed of poly(ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS); a hole-transport layer made of poly[*N*,*N*′-bis(4-butylphenyl)-*N*,*N*′-bis(phenyl) benzidine) (poly-TPD); a light-emitting layer composed of cadmium selenide/zinc sulfide quantum dots (CdSe/ZnS QDs); and a cathode layer composed of eutectic gallium indium (EGaIn). The diameter of the printed QD-LEDs is approximately 2 mm. (Figure adapted from ref. 1.)

The printed devices exhibit brightness, an essential metric of device performance, that is 10- to 100-fold below that of the best solution-processed QD-LEDs[3,8]. However, substantial improvements in device performance are likely to be possible by introducing an electron-transport layer (which was absent in the current architecture), such as one composed of zinc-oxide nanoparticles, and further optimizing the printing process.

The 3D-printing method used by the authors represents a simple, but sophisticated, approach for patterning functional materials. Demonstrated applications of this technique include printing electrodes that interconnect solar-cell and LED arrays[11], 3D antennas[12] and rechargeable microbatteries[13]. Although microbatteries rely on multi-material 3D printing of interdigitated cathode and anode layers, Kong and colleagues' study is much more impressive, because up to six, as opposed to two, different materials must be printed sequentially to create their devices.

One intriguing question that arises is whether fully 3D-printing electronic devices is the best approach for creating mass-customized electronics. Another viable strategy would be to combine 3D printing with automated pick-and-place machinery that places electronic components accurately and repeatably to generate objects with embedded circuitry and devices[11]. LEDs are commercially available that have lateral dimensions akin to those demonstrated by Kong *et al.*, and could be integrated into 3D-printed objects by this hybrid approach.

To vastly expand the capabilities of 3D printing, new functional inks and multi-nozzle print heads and printing platforms must be designed for rapidly and accurately patterning materials over a broad range of compositions and ink-flow behaviour. As these advances are realized, it may be possible to print customized 3D electronic devices in a highly scalable manner. We are becoming increasingly reliant on electronics in our daily lives, and so successful outcomes should be of great benefit to society. ■

Jennifer A. Lewis *and* **Bok Y. Ahn** *are in the School of Engineering and Applied Sciences and the Wyss Institute for Biologically Inspired Engineering, Harvard University, Cambridge, Massachusetts 02138, USA.*
e-mail: jalewis@seas.harvard.edu

1. Kong, Y. L. *et al. Nano Lett.* **14,** 7017–7023 (2014).
2. Colvin, V. L., Schlamp, M. C. & Alivisatos, A. P. *Nature* **370,** 354–357 (1994).
3. Coe, S., Woo, W.-K., Bawendi, M. & Bulović, V. *Nature* **420,** 800–803 (2002).
4. Shirasaki, Y., Supran, G. J., Bawendi, M. G. & Bulović, V. *Nature Photonics* **7,** 13–23 (2012).
5. Smay, J. E., Cesarano, J. III & Lewis, J. A. *Langmuir* **18,** 5429–5437 (2002).
6. Lewis, J. A. *Adv. Funct. Mater.* **16,** 2193–2204 (2006).
7. Wood, V. *et al. Adv. Mater.* **21,** 2151–2155 (2009).
8. Dai, X. *et al. Nature* **515,** 96–99 (2014).
9. Hu, H. & Larson, R. G. *J. Phys. Chem. B* **110,** 7090–7094 (2006).
10. Ladd, C., So, J.-H., Muth, J. & Dickey, M. D. *Adv. Mater.* **25,** 5081–5085 (2013).
11. Ahn, B. Y. *et al. Science* **323,** 1590–1593 (2009).
12. Adams, J. J. *et al. Adv. Mater.* **23,** 1335–1340 (2011).
13. Sun, K. *et al. Adv. Mater.* **25,** 4539–4543 (2013).

J.A.L. declares competing financial interests. See go.nature.com/benofm for details.

ECOLOGY

Deep and complex ways to survive bleaching

Mass coral bleaching events can drive reefs from being the domains of corals to becoming dominated by seaweed. But longitudinal data show that more than half of the reefs studied rebound to their former glory. **SEE LETTER P.94**

JOHN M. PANDOLFI

A constant battle for space is fought every minute of every day on the hard substrates that provide the foundation for living coral reefs. In one corner are reef corals and the photosynthetic dinoflagellate microalgae that live in symbiosis inside them; in the other are fleshy macroalgae, better known as seaweed. On healthy reefs, corals are the clear winners and dominate reef substrates (Fig. 1a). But regime shifts to macroalgae (Fig. 1b) often occur in response to local anthropogenic drivers such as overfishing of herbivores[1] or increased nutrients[2] from pollution and land-use changes — two conditions more favourable for seaweed than for corals. On page 94 of this issue, Graham *et al.*[3] provide the first unequivocal evidence that regime shifts from corals to macroalgae also occur in response to coral bleaching, and they identify aspects of reef ecology that influence the likelihood of this occurring.

Coral bleaching occurs when the coral hosts expel their symbiotic dinoflagellates, which provide much of the vibrant coloration typical of coral reefs. Corals rely on the photosynthetic symbionts for their energy provision, and if bleached corals do not rapidly regain symbionts, they die. Mass bleaching events occur over broad spatial scales and affect a large component of the reef coral community. One such episode, in 1998, is often referred to as the largest mass bleaching event on record[4]; in the Seychelles, more than 90% of live coral cover was lost.