Photonics

Electricity elicits bright light from nanocrystals

Thilo Stöferle & Rainer F. Mahrt

Nanocrystals made from a semiconducting material have been shown to emit intense light when excited with an electric current. The technology could be used to build a type of laser that is more versatile than those in general use. **See p.79**

It's highly likely that you've already been impressed by semiconductor nanocrystals without even knowing it. These tiny, chemically synthesized crystals – also known as quantum dots – have light-emitting properties that are used to produce brilliant electronic displays, and have the potential to form the basis of lasers. But despite their versatility[1], the physical regime required to achieve lasing has so far been induced only by stimulating the crystals with high-powered light sources[2], which precludes many applications. On page 79, Ahn *et al.*[3] report a way of realizing this regime electrically. Although lasing is yet to be demonstrated with this method, the achievement could lead to optical devices operating at wavelengths that are inaccessible to established semiconductor materials.

For a semiconductor crystal to produce light, one of its electrons must first be excited from a low-energy state into one of higher energy. When this happens, the electron can undergo a process called spontaneous emission: it returns to its initial state and releases the energy it has gained as a photon, the wavelength of which is defined by the energy difference between the two states. A photon with this wavelength can also induce emission of a second photon with the same wavelength, if the material remains in an excited state while the first photon is passing through it. This is known as stimulated emission, and it effectively amplifies the flux of photons of a given wavelength. If enough electrons are excited, the number of photons generated can exceed those lost in the material, leading to optical amplification – an avalanche-like effect that results in intense light of a certain colour.

A material can be excited optically by hitting it with photons, but the task can also be achieved with an electric current. The idea is that negative and positive charge carriers (electrons and holes) are injected into the material and pair up, causing the electrons to merge with the holes and undergo spontaneous emission. Yet electrically driven optical amplification of nanocrystals has remained out of reach for decades[4]. There is no single reason for this – instead, there are myriad challenges that combine to make it difficult to achieve. Ahn and co-workers have succeeded in engineering a device that overcomes all these issues at the same time (Fig. 1).

> **"The authors' device is a result of amplified spontaneous emission – a key step towards lasing."**

The first problem is one of scale: the size of the nanocrystals determines the wavelength of light they emit, so maintaining uniform, nanometre-sized crystals is crucial for achieving colour purity. However, to reach the amplification regime, it is necessary to cram many charge carriers into these tiny crystals. This overcrowding dampens the excitation, thereby reducing, instead of amplifying, the emission[5]. By changing the composition of the nanocrystals gradually from the core outwards, members of the same research group as Ahn *et al.* previously alleviated this problem, ensuring that the charge carriers were not confined as strongly as they would be in a uniform crystal[6]. And by using compact nanocrystals, they maximized their packing density, which increased the total optical emission.

The second challenge involves the electrodes that deliver the positive and negative charge carriers to the device. In general, electrodes that are electrically conductive enough for the task are also prone to absorbing photons themselves. Ahn *et al.* therefore separated the electrodes and the nanocrystals by inserting intermediate layers that allowed very little of the emitted light to go near the electrodes. Small apertures were used to focus the current flow directly through the nanocrystals, preventing photon losses owing to stray charge carriers.

The team also engineered a layered structure that minimized the light radiating vertically from the device, thereby maximizing emission from the intended output side. Previous architectures[7,8] have featured glass substrates that rely on total internal reflection to guide the light towards the output edge, but such structures are subject to large optical losses. The authors' layered architecture enabled constructive interference to

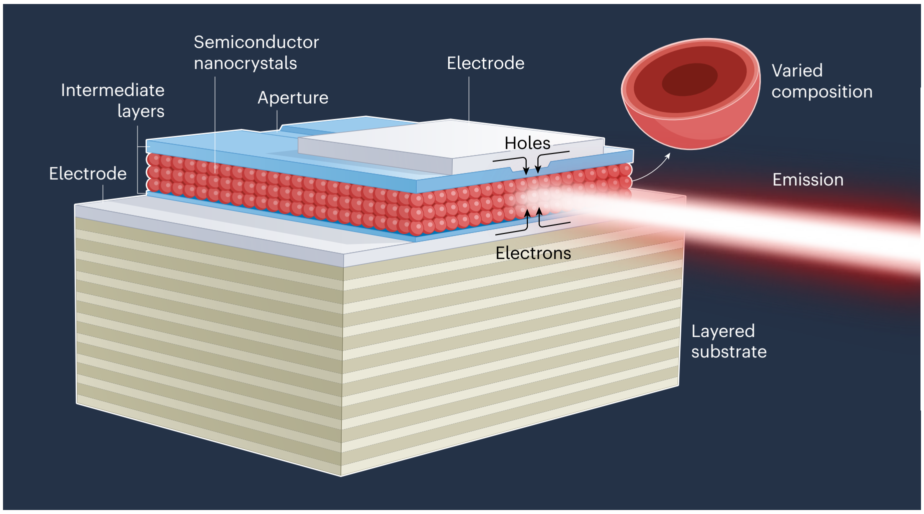

Figure 1 | An electrically driven device that emits bright light. Ahn *et al.*[3] built a device that uses negative and positive charge carriers (electrons and holes, respectively) to induce semiconductor nanocrystals to emit intense coloured light. The authors changed the composition of the nanocrystals from core to surface to prevent carrier losses, which can reduce the amount of light emitted. In the device, intermediate layers were used to separate the nanocrystals from the current-supplying electrodes, which tend to absorb photons, and apertures in the intermediate layers focused the current directly through the nanocrystals. A layered substrate maximized light emission from one side of the device. These innovations enabled the device to undergo a process called amplified spontaneous emission, which means that it could form the basis of an electrically driven laser. (Adapted from Fig. 3 of ref. 3.)

substantially reduce these losses and further limit photon absorption in the electrodes.

By optimizing their device in this way, Ahn *et al.* were able to achieve electrically excited emission with the intense brightness and narrow wavelength spectrum characteristic of optical amplification. They also observed that the device enhanced several of the light's properties, including its polarization, coherence (the degree to which the light waves are in step with each other) and directionality (the degree to which the light is emitted in a single direction). These features indicate that the bright light emanating from the edge of the authors' device is a result of amplified spontaneous emission — a key step towards lasing.

Amplified spontaneous emission has already been achieved with nanocrystals through optical excitation, and been used extensively in laser devices in the past two decades. Electrically driven spontaneous emission has also been realized — in fact, it forms the basis of the common light-emitting diode (LED). However, Ahn and colleagues' device is the first to reach the amplified regime. And its nanocrystals can be deposited simply (using a process similar to inkjet printing, for example), thereby avoiding the high-temperature and vacuum conditions required to deposit the crystals used in conventional semiconductor devices.

However, amplified spontaneous emission differs in several aspects from laser emission. To realize an actual laser, Ahn and co-workers would need to narrow the spectrum of emission from their device, lengthen the time over which the light maintains coherence and ensure that the beam is less divergent. To achieve this, they would need to add a device known as a resonator structure, which is beyond the scope of the present work. The output of the device is currently far from that exhibited by conventional semiconductor lasers, but it's important to note that such lasers have been improved by researchers in industry and academia continually over the past six decades. Even so, because such lasers rely on specific semiconductor materials of high quality, there are limits to their versatility in terms of how easily they can be integrated into electronic devices, and the wavelength (colour) ranges that are available.

This is where electrically driven nanocrystal lasers could shine. It could well be that future use of nanocrystals will not be restricted to bright display screens, but might involve other applications that require lasers[9], such as compact sensing or communication. Ahn and colleagues' achievement in realizing electrically driven optical amplification of semiconductor nanocrystals could also inspire researchers working on organic lasers, from which the authors derived some inspiration of their own. In any case, whether they are made from colloidal quantum dots or organic materials, such unconventional integrated lasers driven exclusively by electricity would indeed be a game-changing technology.

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Tumour biology

Enzyme lights dual fires to promote cancer

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Tumours with certain cancer-driving mutations are difficult to treat. A discovery that one enzyme both controls proliferation and suppresses anticancer immune defences presages the exploration of new cancer-therapy strategies. **See p.139**

The legendary forces of the Universe — such as fire and water, or light and darkness — are in perpetual balance, and in mythology, disruptions in this balance cause mayhem. In cells, disruption in the delicate balance between two opposing types of enzyme, kinase and phosphatase, also leads to chaos. Kinases light cellular signal flares by adding phosphate groups to targeted proteins, and this action is doused by phosphatases, which remove the phosphates. One such opposing pair is the kinase PI3Kβ and the phosphatase PTEN, which together profoundly affect cellular and organismal fate. On page 139, Bergholz *et al.*[1] demonstrate that an imbalance between PI3Kβ and PTEN not only drives proliferation of tumour cells, but also strongly promotes tumour evasion of immune-system defences, leading to breast cancer progression and resistance to state-of-the-art cancer immunotherapy. The authors show how powerful tumour-promoting mutations can initiate signalling cascades that stimulate tumour-cell proliferation and immunosuppression, and identify a single therapeutic strategy that can control both pathways.

> **"This insightful work shows how loss of the PTEN protein controls both tumour immunosuppression and proliferation."**

One of the most common cancer-promoting (driver) mutations in people who have tumours results in the loss of PTEN, a tumour suppressor[2]. PTEN loss allows unchecked PI3Kβ signalling, which leads to the survival and proliferation of tumour cells and results in cancer growth[3]. However, aberrant cell proliferation alone is not usually sufficient to promote tumour development — a cancer must also have strategies for withstanding a barrage of hostile attacks by the immune system that can kill tumour cells. Aggressive tumours can evade the immune system (immune evasion) in three ways: by establishing barriers that prevent cell-killing immune cells called cytotoxic T cells from entering tumours; by overstimulating cytotoxic immune cells (resulting in a dysfunctional immune-cell response termed exhaustion); or by activating immune cells that dampen the immune response. However, little is known about how most tumours directly promote such immunosuppression.

Through comprehensive studies of mouse PTEN-deficient breast cancer cell lines grown *in vitro*, Bergholz and colleagues show that PTEN loss activates PI3Kβ, which directs a bifurcated signalling pathway: one branch promotes tumour growth by signalling through a kinase called AKT to boost cellular survival and proliferation; the other enables immunosuppression mediated by a transcription factor called STAT3 (Fig. 1).

STAT3 has well-characterized roles in repressing the expression of pro-inflammatory signalling molecules called cytokines, and in promoting the expression of immunosuppressive cytokines[4,5]. The authors report that the inhibition of PI3Kβ or STAT3 by gene