molybdenum and tungsten dichalcogenides, some of which have been predicted to have larger piezoelectric coefficients than MoS_2 (ref. 3). Piezoelectricity has been reported in few-layer C_3N_4 nanosheets[7].

Future work may involve the study of higher-order electromechanical effects in few-layer materials that have potential to generate curvature in membranes[5]. The atomically thin nature of these materials also provides avenues to endowing non-piezoelectric materials with piezoelectric properties through the adsorption of adatoms or molecules that change the local symmetry of the material. Graphene has an inversion centre and is not piezoelectric, but the single-sided adsorption of adatoms has been predicted to provide it with some non-zero elements of the piezoelectric tensor[8].

Two-dimensional piezoelectric materials could improve the performance of piezoelectrics in existing applications, such as surface acoustic wave devices. These materials may also enable new applications due to their nanoscale nature. For example, it might be possible to achieve integration of electronic and acoustic elements in a single layer. Furthermore, very large tensile strains of more than 20% have been reported in two-dimensional materials, pointing to the potential for applications in flexible electronic devices. In fact, Wang and colleagues suggest that two-dimensional piezoelectrics could be used for energy harvesting[1].

The piezoelectric effect may also play an important role in the function of devices whose operation is not based on piezoelectricity. For example, in GaN/AlN superlattices, which are used to make optoelectronic devices, the interface between the layers can host two-dimensional electron or hole gases that result from piezoelectric effects. Similarly, such effects could also play a role in interfaces between two-dimensional materials.

Practical applications for single-layer and few-layer piezoelectrics will be facilitated by the fabrication of larger-area single crystals, which are currently at micrometre length scales. Another challenge may be the precise control of the required layer thickness, which is needed because of the sensitivity of the piezoelectric effect to the number of layers in the material. ❐

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NANOSTRUCTURED LASERS

Electrons and holes get closer

Nanowires that exhibit very sharp emission due to the formation of quantum states within them have been used to fabricate low threshold current lasers emitting ultraviolet light.

Chee-Keong Tan and Nelson Tansu

The 2014 Nobel Prize in Physics was awarded for the development of blue-emitting InGaN-based light-emitting diodes (LEDs)[1]. In the past two decades, substantial progress has been made in the field of visible LEDs driven by both materials[2,3] and device innovations[4–7] in InGaN-based platforms. Extending this type of progress to the development of electrically driven light sources in the mid-UV (~270–320 nm) and deep-UV (~220–270 nm) would result in a range of important device applications in the fields of water purification, bioagent detection, data storage and non-line-of-sight communications. But it has been quite difficult. The material of choice at those wavelengths is $Al_xGa_{1-x}N$, and its fundamental optoelectronic properties are still not fully understood. The progress in electrically injected diodes emitting in the mid- and deep-UV spectral regimes had been limited to ~336 nm for room-temperature operation[8], primarily attributed to the poor material gain in the active region operating near this regime. Now, writing in *Nature Nanotechnology*, Zetian Mi and colleagues from McGill University report[9] the fabrication and performance of electrically driven lasers based on $Al_xGa_{1-x}N$ core–shell nanowires. These lasers emit at 334 nm and work at a temperature of 6 K. One of the key elements for this achievement is the diffusion-driven compositions within the nanowires, which leads to electrons and holes recombining more efficiently than usual. A second is that the arrangement of these wires in randomly distributed arrays forms a high-*Q* resonator cavity.

In light-emitting devices and lasers, when an electrical current flows through the device, electrons and holes are injected from negatively and positively charged electrodes, respectively, into the so-called active layer, which is often a quantum well (QW), a thin layer (around 2–3 nm) of material where the electrons and holes are confined. The electrons and holes recombine to generate photons, with the rate proportional to the square of the electron–hole spatial coupling within the layer — which is often referred to as the electron–hole overlap[4]. The issue with nitride semiconductors is that their atomic structure gives rise to large and orientation-dependent polarization fields. More specifically, this structure follows a hexagonal cylinder pattern, and the polarization is maximum along the cylinder and zero along the perpendicular direction. Because of this polarization field, electrons and holes are spatially separated within the active layer, a characteristic often referred to as charge separation. As a consequence, the level of current density, known as the threshold current density, that has to flow through the devices before lasing can be achieved, is very high.

In the case of the $In_xGa_{1-x}N$ and $Al_xGa_{1-x}N$ systems, the charge separation in polar *c*-plane QWs (Fig. 1a,b) can be addressed by using so-called large-overlap polar QWs[4,5] or semi/non-polar QWs[6,7]. The potential energies can be modified based on the nanostructure design along the QW growth direction (Fig. 1a,b) resulting in the ability to modify the shape of the carrier wavefunction, which represents the probability density of its spatial distribution in the active

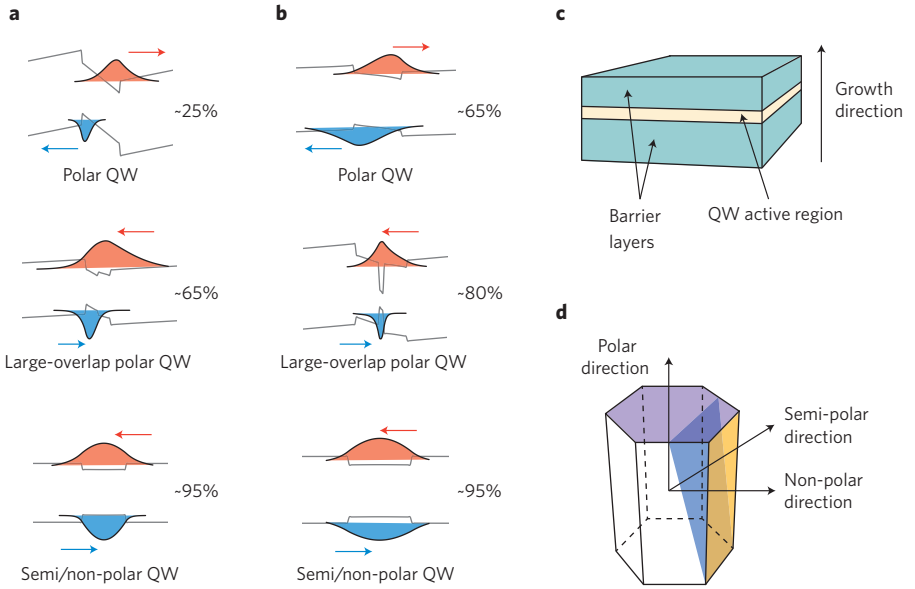

Figure 1 | The distributions of electron and hole wavefunctions, with the associated growth and crystal orientation for III–nitride QWs. **a**,**b**, Charge separation and the strategies to address this issue in InGaN visible QWs (**a**) and AlGaN UV QWs (**b**). The potential energies (vertical axes) are plotted against the spatial position (horizontal axes) along the growth directions (grey lines), with the corresponding carrier wavefunctions (red for electrons and blue for holes) and the overlap values, which are expressed as a percentage. The red and blue arrows represent the directions of the pulling of electrons and holes within the QWs, respectively. A poor overlap value corresponds to strong charge separation in nitride active regions. Nanostructuring can pull electrons and holes closer to each other, resulting in improved overlap values. **c**,**d**, The growth directions (**c**) and crystal orientations (**d**) are shown for polar and semi/non-polar active regions.

region. The large-overlap active region can be achieved by intentionally designing the shape of the QW — step-like[4] or linearly graded shaping[5] along QW growth direction — that results in keeping electrons and holes closer together. The semi-[6] or non-polar[7] QWs can be realized by growing the active layer in the orientation off-axis from the cylindrical direction (Fig. 1c,d), which results in partial or full removal of the polarization fields, respectively. The structures investigated by Mi and co-workers consist of core–shell $Al_xGa_{1-x}N$ nanowires, in which the shell has a higher Al content than the core[9]. The nanowires were grown using a catalysis method driven by strain mismatch between the $Al_xGa_{1-x}N$ and silicon substrate in a molecular beam epitaxy reactor chamber. This process results in a highly packed density of nanowires in the form of hexagonal cylinders with vertical ordering and relatively random positions. The distribution of the Al/Ga ratio is shown to vary in a linearly graded profile as shown in the compositional analysis of the active region (Fig. 2). This linearly graded profile can be attributed to the diffusion-driven process in the QW active regions. The Al/Ga composition profile also reveals the existence of quantum dot structures that are formed as a result of the local potential minima both along the axial and radial directions (Fig. 2). The quantum dots formed within the nanowires are primarily due to the one-dimensional decreasing linear distribution of the Al/Ga composition with a minima at the centre of the active region, as well as a monotonically decreasing Al/Ga ratio from the outer surface of the wire to the centre along the radial direction. Such profiling in the diffusion-driven $Al_xGa_{1-x}N$ quantum dots[9] is analogous to the linearly graded compositional QWs[6], and results in a large overlap and improved carrier confinement. Specifically, the overlap in the $Al_xGa_{1-x}N$ system can be improved by 1.2–1.5 times by using the profiling method (Fig. 1b). The quantum dots coupled with a high-*Q* cavity formed in the nanowire-array random cavity results in very low threshold current density at a temperature of 6 K.

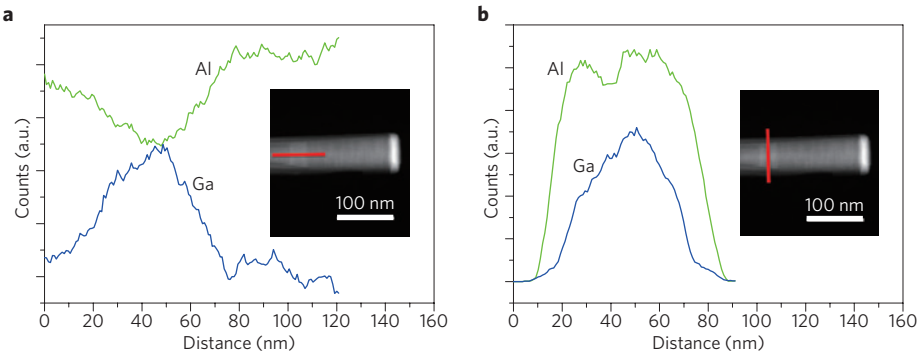

Figure 2 | The compositional distribution in the three-dimensional active region within the AlGaN-based nanowire. **a**,**b**, The linearly graded compositional distribution of Ga/Al along the axial (**a**) and the radial (**b**) directions. The compositional distribution was obtained from the energy dispersive X-ray spectrometry line scan across the active region in the respective directions, as shown in the insets. Figures adapted from ref. 9, 2015 Nature Publishing Group.

The presence of the quantum dots within the AlGaN-based nanowires is essential for the fabrication of such low-threshold devices. Unfortunately, electrons and holes are confined within these dots only very weakly, which is a serious obstacle for working at temperatures higher than 6 K, especially if room-temperature operation is desired. This work enables the future development of nanowire technologies taking advantage of diffusion-driven linear-grading quantum dots for enabling electrically driven deep-UV lasers at low temperature. Despite its current limitation, this finding shows important value for the community in the pursuit of high-*Q* random lasing in electrically injected mid-UV nanowire-based lasers. High-temperature operation of such lasers can be pursued specifically by improving the carrier confinement and gain properties in the active regions of the nanowire lasers.

Although the results are promising as a proof of concept for low-threshold lasers emitting at low temperature, significant challenges still exist to develop high-power practical device technologies for achieving lasing at room temperature. The characteristic of such high-*Q* random lasing devices[9] is associated with the local lasing from such devices resulting in the low pumping threshold current exhibited at the expense of low output power. The

three-dimensional linearly shaped quantum dots made via the diffusion-driven process[9] favour large overlap between the electron and hole wavefunctions. Thus, this finding is exciting for the community to investigate the approach of playing with the cavity design and shaping the 'active region' in nanowires for lowering the threshold current density and achieving high-efficiency mid- or deep-UV lasers.

Another important limitation of the high-Al-content $Al_xGa_{1-x}N$-based emitter is the significant band-filling effect attributed to the cluttering of valence sub-bands at specific compositions of active regions emitting near the emission wavelength of 320–330 nm (ref. 10). Owing to this large number of valence sub-bands stacking at relatively similar energy levels, the amount of carriers required to be pumped into the active region increases significantly to achieve acceptable optical gain for lasing. In most cases, the amount of carriers is too large to achieve sufficient optical gain to overcome optical losses in the cavity resulting in an inability to realize the electrically driven lasers at wavelengths shorter than 336 nm (ref. 8). Perturbing a nanostructure by using an ultrathin GaN delta layer has been shown to dramatically increase the gain[11,12]. ❐

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FERROELECTRIC NANOSTRUCTURES

Domain walls in motion

Voltage pulses can be used to controllably displace ferroelectric domain walls at the nanoscale.

Jan Seidel

Natural and artificial interfaces in ferroic materials are of special interest because local changes in symmetry and structure at the interface can lead to additional functionality not present in the parent bulk material. Domain walls are one possible type of such interfaces that separate regions of different orientations of the specific order (such as magnetic, ferroelastic or ferroelectric) in the material[1]. Natural interfaces such as domain walls are intrinsically very small, of the order of 1 nm in ferroelectrics. Their size and the fact that they can be moved by applied external fields makes them attractive as functional nanoscale features. With oxide nanoelectronics on the rise[2], the fundamental understanding and utilization of electronic properties of domain walls in complex oxides has recently received considerable interest, after electrically conductive walls were reported[3]. Applications relying on such conducting domain walls would benefit considerably if the walls could be precisely created and moved dynamically on the nanoscale. Towards this end, it has been shown that electric fields around fixed structural inhomogeneities can be used to nucleate ferroelectric domain walls at specified locations[4].

Writing in *Nature Nanotechnology*, Leo McGilly and colleagues at École polytechnique fédérale de Lausanne (EPFL) have now shown that ferroelectric domain

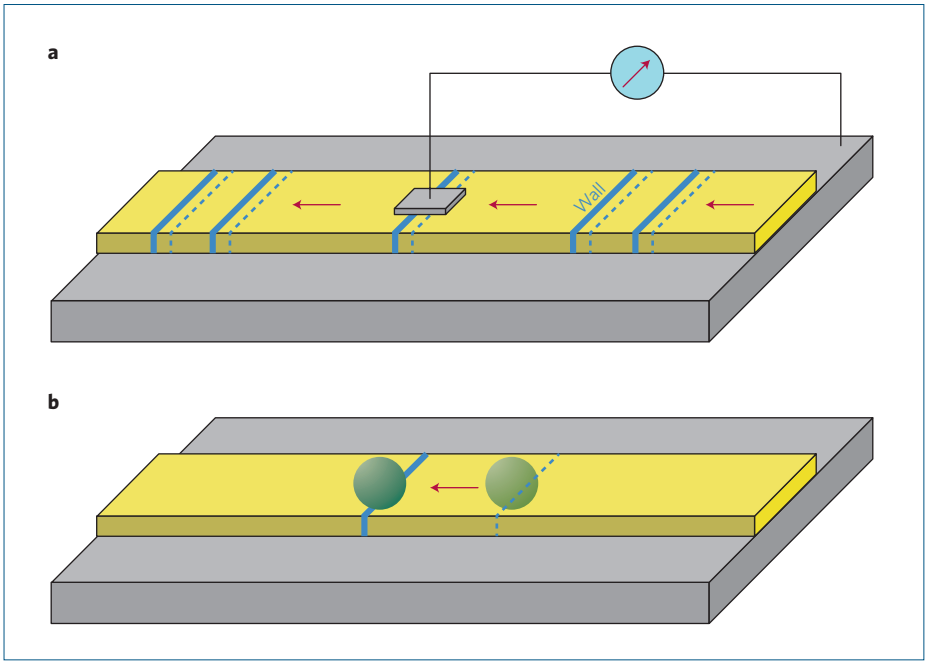

Figure 1 | Domain walls as information and nanoobject carriers. **a**, Schematic of a ferroelectric domain wall shift register or ferroelectric domain wall 'racetrack' (analogous to a magnetic racetrack memory)[5]. Walls are moved by electric fields, and information is readout by a suitable domain wall detection mechanism (for example, by utilizing higher domain wall conductivity with regard to the bulk material). **b**, Schematic of a domain wall as a nanoscale conveyor for the transport of nanomaterial, which would require a suitable mechanism for binding the nanoobject (green sphere) to the domain wall. The red arrows indicate the direction of motion of the domain walls from an initial position (dotted line) to a final position (solid line) after application of an electric field. Yellow, ferroelectric material; grey, electrodes.