Site-controlled quantum dot arrays in waveguides for quantum technology applications

InAs/GaAs quantum dots (QDs) have optical properties that make them excellent quantum emitters, including bright emission with narrow linewidths. Research from the NEF, together with colleagues from the Low Dimensional Structures and Devices group in the School of Mathematical and Physical Sciences at the University of Sheffield (https://ldsd.sites.sheffield.ac.uk/), has demonstrated their incorporation into waveguides, with observation of on-chip Hong-Ou-Mandel interference [1], high Purcell factor generation of indistinguishable photons [2], chiral coupling of QDs to a waveguide, giving unidirectional transfer of spin information [3] and enabling the construction of quantum photonic circuit elements including topological add-drop filters [4].

InAs QDs are normally formed by Stranski-Krastanov growth, a strain-driven process where islands form after a thin layer of InAs is deposited on GaAs, and once these islands are capped they provide localised 3D confinement of electrons and holes within the semiconductor. However, the position of these islands is random (figure 1a) so they have to be located and registered in order to place them in an optical circuit in an optimum position, limiting the number of QDs that can be incorporated. For a scalable solution, we have been developing arrays of site-controlled QDs, where the QDs are preferentially nucleated on a patterned surface (figure 1b), formed of a series of nanoholes defined by electron-beam lithography (EBL) or local anodic oxidation (LAO) using an atomic force microscopy (AFM) tip.

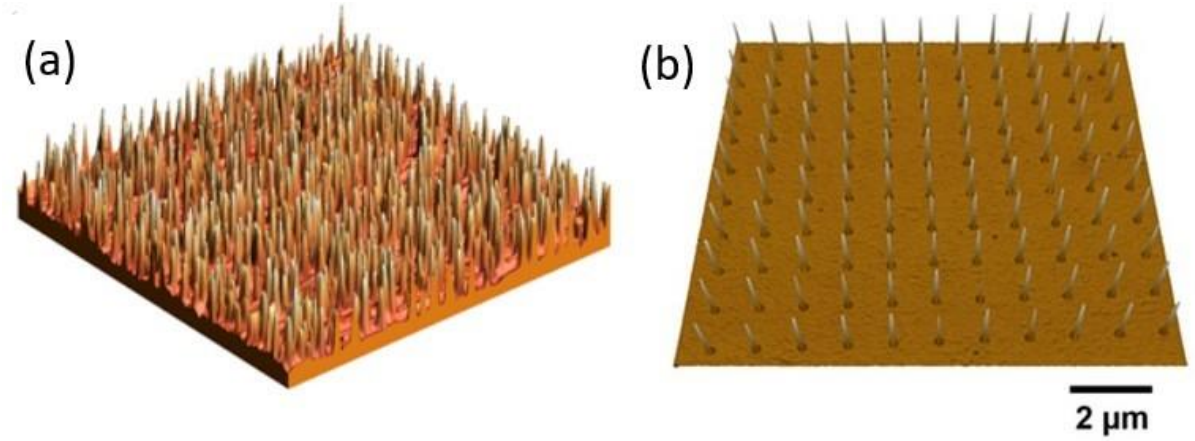

Figure 1: (a) 5 µm x 5 µm (x 20 nm) AFM image obtained from an uncapped layer of InAs/GaAs QDs grown by the Stranski-Krastanov method, (b) 10 µm x 10 µm AFM image showing preferential nucleation of QDs in an array of nanoholes.

Methodology

Partial device structures, including sacrificial etch layers for suspended waveguide formation and doped semiconductor layers for electrical contacting, are grown and removed from the molecular beam epitaxy (MBE) system. The sample is then patterned with arrays of nanoholes where the size and depth of the holes are varied as well as the pitch of the array. Once patterned, the sample is cleaned with a series of solvent cleans and an oxide removal dip. The sample is then reloaded into the MBE cluster tool (figure 2), which is fitted with a secondary ion mass spectrometry (SIMS) system for checking the cleanliness of the sample surface. Following an initial cleanliness check the sample is transferred to a cleaning chamber for hydrogen cleaning for further contaminant and oxide removal, which can be carried out at a lower temperature than conventional thermal desorption of the oxide, so maintaining the nanohole pattern. The sample is then rechecked by SIMS before transfer to the growth chamber for deposition of a thin buffer layer, the QD layer and the rest of the device structure.

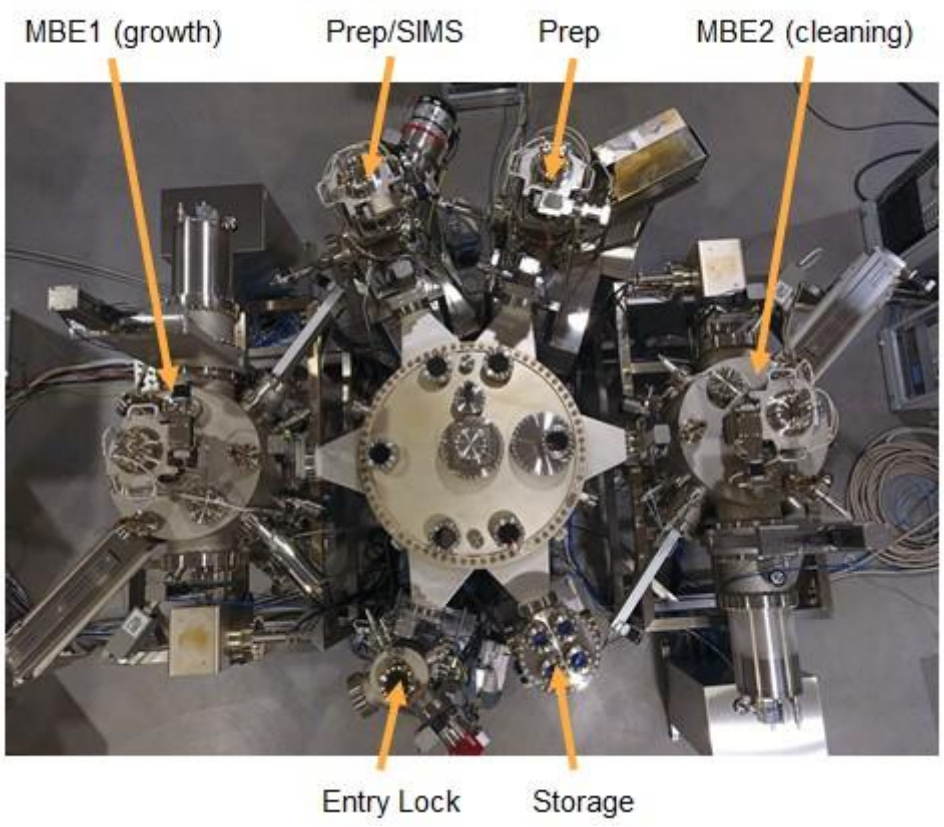

Figure 2: Overhead view of the DCA Instruments MBE Cluster Tool, showing the locations of various process chambers

Challenges

An ideal ordered array should contain a single QD per nanohole of uniform size and shape, to achieve similar emission wavelengths from each QD, and we wish to preserve their narrow emission linewidth, which corresponds to increased exciton coherence time. Although nucleation in the nanoholes may lead to a narrower size distribution of QDs than for growth on a planar surface, the inhomogeneous broadening of the QD ensemble is still larger than the tuning range of the emission wavelength of single QDs by applied fields. The emission linewidth is affected by charge noise from nearby defects, interfaces or carriers in other QDs. QDs buried in thick GaAs layers, where there are no nearby interfaces, can exhibit linewidths <2 μeV and we have demonstrated linewidths of 3.1 ± 0.2 μeV for QDs in waveguides [5], despite the thin GaAs membrane required for single mode operation (typically 170 nm). The patterning process can introduce damage to the semiconductor that will act as charge traps and emission linewidths from site-controlled QDs typically far exceed those for QDs grown on pristine surfaces (>100 μeV). Optimisation of the buffer layer, regrown above the patterned surface before the QD layer is deposited, is required to minimise any degradation in the linewidth. Other techniques including stacking QDs and growth on patterned ridges to promote anisotropic growth can be used to seed an optically active QD further away from the patterned surface, yielding linewidths <10 μeV [6, 7]. However these strategies may not be suitable for particular device geometries, especially for the thin membranes required for single-mode waveguides.

Careful control of growth conditions is required for nucleation of single QDs in each nanohole with high occupation probability, and these conditions have to be optimised depending on the array parameters, which may vary (particularly in array pitch) depending on application. Once the QDs are

formed, subsequent growth of the device must allow for planarization of the surface while fitting into confined thickness of waveguide for single mode operation.

Solutions

We have carried out extensive studies to optimise growth conditions arrays of different parameters to achieve single occupancy, particularly controlling the InAs coverage in order to obtain QD nucleation in the nanoholes but avoiding nucleation between the patterns. Figure 3(a) shows photoluminescence from a set of nanohole arrays, defined using varying draw size and dose by EBL in order to vary the nanohole diameter and depth. For the majority of arrays, a high site occupancy of optically active QDs is obtained, with low levels of QD nucleation outside of the patterned areas. Similar experiments can identify optimum conditions for QD deposition over a range of array pitches, controlling the QD density required depending on the device requirements.

Depending on growth conditions, the low temperature emission wavelength of the GaAs-capped site-controlled QDs can vary from 900-1200 nm. Typically we target emission <1000 nm in order to be compatible with highly responsive Si photodetectors, so we need to tune the emission of the QDs to this range. This is done by controlling the height of the QDs using a partial capping technique, where a thin GaAs cap (a few nm) is grown at the same temperature as used for the deposition of the QDs before increasing the temperature to desorb any remaining In on the surface and truncating the height of the QDs, then resuming growth of the GaAs cap. This yields bright single QD emission in the target wavelength range (figure 3(b), obtained from a site-controlled QD located 30 nm from the regrowth interface) with much narrower linewidths than typical for single layers of site-controlled QDs. The narrowest linewidth so far obtained for these QDs are 26 µeV for an array defined by EBL and 33 µeV for an array defined by LAO, close to the resolution limit of the photoluminescence system. Further reduction in linewidth could be expected, for example by use of stacked QD layers. These QDs have been incorporated into waveguide p-i-n devices, where a Stark-effect tuning range of 5 nm has been observed, and sets of neighbouring QDs with emission wavelengths within this range have been identified. Optimised growth conditions, particularly controlling As pressure during capping, has achieved planarization of growth within the 170 nm GaAs membrane for low-loss waveguide fabrication. These devices are currently being characterised by our research collaborators.

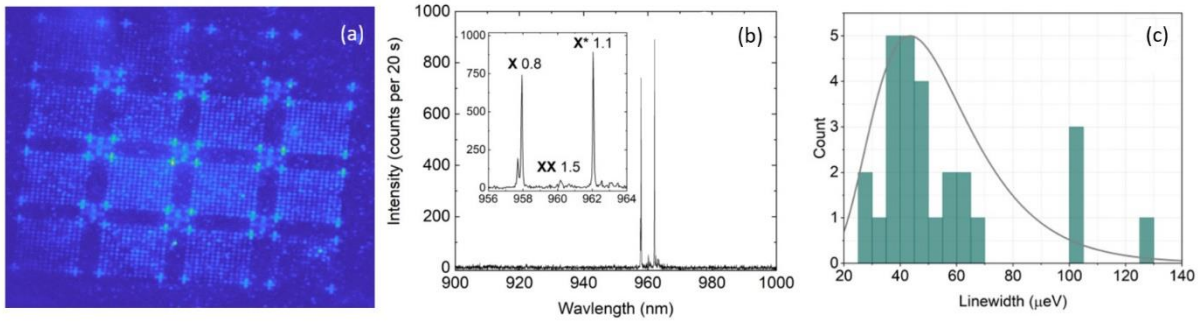

Figure 3: (a) PL image obtained over a wavelength range of 900-975 nm, showing PL from QDs in a set of nanohole arrays with high site occupancy, (b) Micro-PL obtained from a site-controlled QD, with (inset) exciton, biexciton and exciton complex emission peaks identified, (c) emission linewidth distribution from an array of site-controlled QDs, with some near the resolution limit of the PL system.

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