

Annealing InP quantum dot MBE structures for laser

Researchers achieve threshold current density comparable to MOCVD structures.

Researchers in the USA report progress in molecular beam epitaxy (MBE) and post-growth annealing of indium phosphide (InP) quantum dot (QD) structures for deployment in near-infrared and visible red laser diodes with low threshold current density (J_{th})

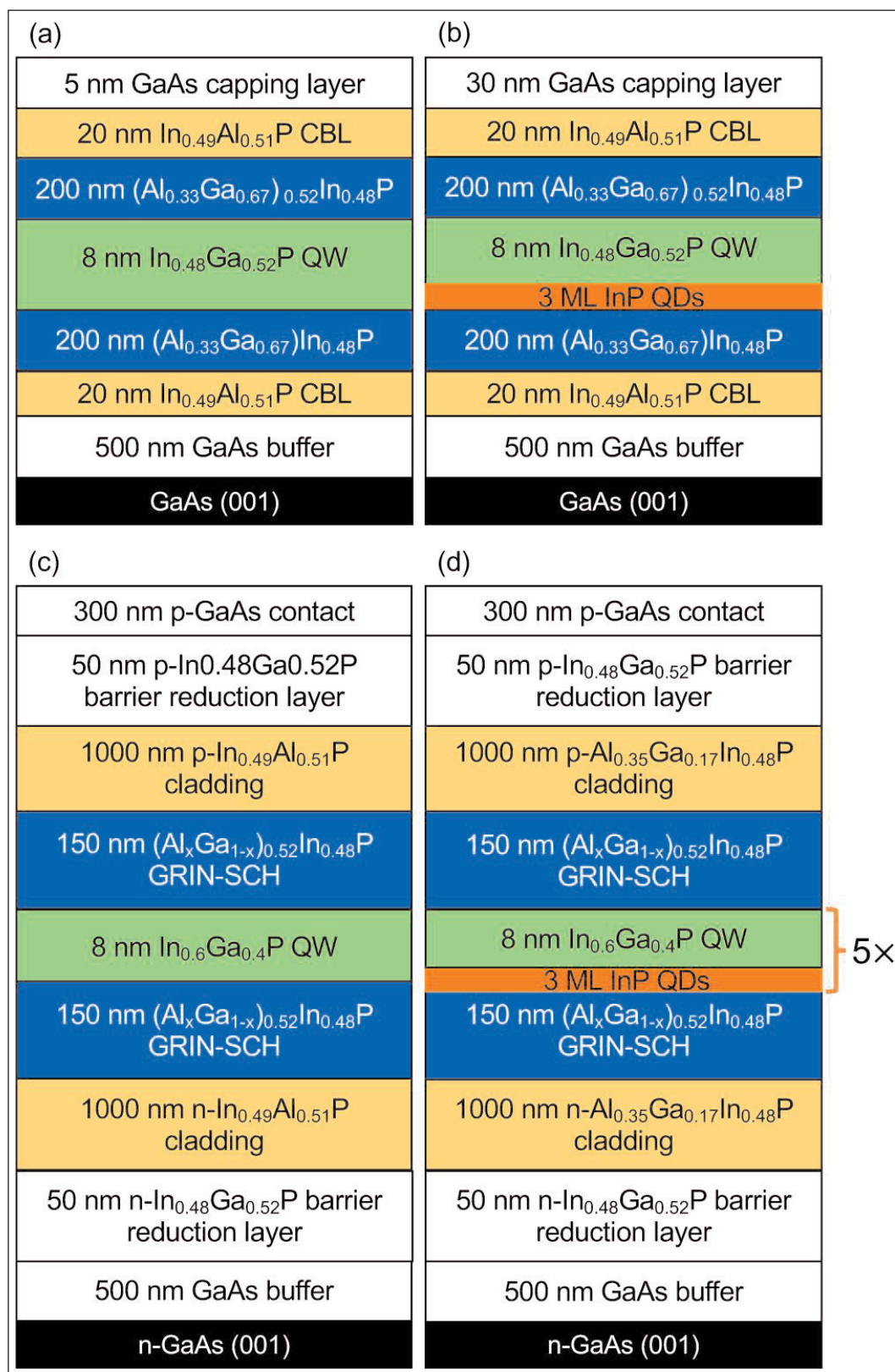
[Pankul Dhingra et al, J. Appl. Phys., v133, p103101, 2023].

“After annealing, J_{th} per QD layer is $99.8\text{A}/\text{cm}^2$, $>7\times$ lower than previous reports by MBE and comparable to their MOCVD-grown counterparts,” claims the team from University of Illinois Urbana-Champaign and University of Texas at Austin.

The researchers add: “Among the few reports of the molecular beam epitaxy (MBE) growth of InP QD lasers, the lowest published J_{th} value is $\sim 2000\text{A}/\text{cm}^2$, $>10\times$ higher than with MOCVD.”

The low growth temperature of MBE relative to metal-organic chemical vapor deposition (MOCVD) leads to challenges in terms of optical quality of the complete epitaxial structure, which included quaternary aluminium gallium indium phosphide (AlGaInP) alloy barriers for the InGaP

Figure 1. PL structures for (a) $\text{In}_{0.48}\text{Ga}_{0.52}\text{P}$ QW and (b) InP QDs grown on GaAs (001) substrates. Laser design for (c) $\text{In}_{0.6}\text{Ga}_{0.4}\text{P}$ SQW and (d) InP MQD graded-index separate-confinement heterostructure (GRIN-SCH) lasers.



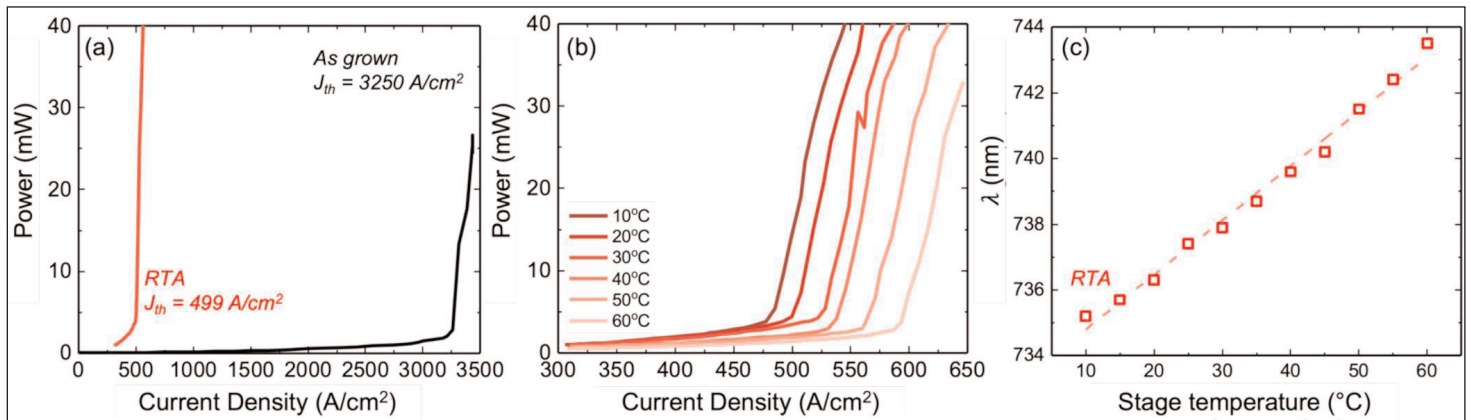


Figure 2. (a) Pulsed light output power–current density characteristics of InP MQD laser at room temperature. (b) Temperature-dependent performance. (c) Temperature dependence of emission wavelength.

quantum wells (QWs) in which the QDs were placed.

The team reports: “InP/AlGaInP QDs show greater thermal stability, with ~50x increase in the PL intensity due to improvement in the optical properties of InP QDs, InGaP QWs, and AlGaInP barriers. Thermal annealing is a crucial step toward developing visible red lasers that will allow integrated photonics to expand into areas such as quantum computing, optogenetics, and next-generation displays.”

The researchers add: “While the atomic origin of the improvement remains unclear, deep-level transient spectroscopy studies of InGaP/AlGaInP QWs show a substantial reduction of signals related to phosphorous vacancy complexes after rapid thermal annealing (RTA) at 875°C.”

The attraction of MBE is that it allows easier growth control of the QD layers themselves. In MOCVD, the substrates need to be offcut to encourage high dot density with uniform size.

The researchers grew four solid-source MBE structures on gallium arsenide (GaAs) (001) substrates with a view to photoluminescence (PL) and laser diode (LD) experiments (Figure 1). The substrate temperature during the growth was 460–480°C. The V/III ratio was in the range 15–30.

For the PL experiments, the protective GaAs capping layer was removed by etching. The QW and three monolayer (ML) QD active regions were sandwiched between carrier-blocking layers (CBLs) consisting of undoped indium aluminium phosphide (InAlP) to reduce surface recombination. The well barriers were AlGaInP rather than the more usual InGaP.

These layers translated with suitable doping and thickness/composition adjustments into suitable components of the laser diodes. Some of the adjustments aimed at creating compressive strain in the QW — rather than the unstrained condition of the PL structure — with a view to reducing the threshold current of the broad-area stripe lasers with 800–1560 μm cavity lengths. The laser mirror facets were uncoated.

The PL study focused on tuning the post-growth

annealing, aiming at high-intensity, stable wavelength emission from the structures. The team performed comparisons based on rapid thermal annealing (RTA) and furnace annealing (FA) techniques. The use of quaternary AlGaInP barriers reduced indium out-diffusion, enabling longer annealing times at higher temperature.

Laser diodes fabricated from the single-quantum-well (SQW) epitaxial material had 1.5x reduced threshold current density, from 340 to 200 A/cm², after RTA at 950°C for 1s. Using a heat-sink, the threshold current was maintained at 200 A/cm² even in continuous-wave operation, “among the lowest reported values for In_{0.6}Ga_{0.4}P SQW lasers by any growth technique”, the team points out. The RTA blue-shifted the as-grown emission wavelength from 690 nm to 683 nm.

The researchers comment: “Changes in the emission wavelength can be attributed to group-III intermixing after RTA, heating of the active region at high current density, and current-induced wavelength shift, typically observed in broad-area lasers.”

The same RTA process reduced the threshold current density by 6.5x, from 3250 A/cm² to 499 A/cm², in the multiple quantum dot (MQD) laser structures (Figure 2). Measurements of the threshold between 10°C and 60°C gave a characteristic temperature of 230 K for the RTA laser diodes, representing an increase from 477 A/cm² to 586 A/cm² with temperature.

The researchers comment on the temperature-dependent measurements, “there are no previous reports describing the high-temperature operation of MBE-grown InP QD lasers for comparison to these results.”

The near-infrared (NIR) wavelength of the RTA MQD lasers also red-shifted with temperature. The as-grown InP MQD lasers did not operate past 20°C.

Unspecified “further improvements in the fabrication” and heat-sinking enabled continuous-wave operation of annealed MQD lasers with 565 A/cm² threshold.

The researchers expect similar performance gains from furnace annealing, based on their PL studies. ■

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