All III-Arsenide Low Threshold InAs Quantum Dot Lasers on InP(001)

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Abstract

This study investigates the development of InAs quantum dot (QD) lasers on a InP(001) substrate, utilizing only III-arsenide layers. This approach avoids the issues associated with the use of phosphorus compounds, which are evident in the crystal growth of conventional C/L-band QD lasers, making the manufacturing process safer, simpler, and more cost-effective. The threshold current density of the fabricated QD laser was 633 A/cm2, which is the lowest value for QD lasers in the 1.6 µm-wavelength region. This result suggests a high cost-effectiveness and paved the way toward a large-scale production technology for high-performing C/L/U-band QD lasers.

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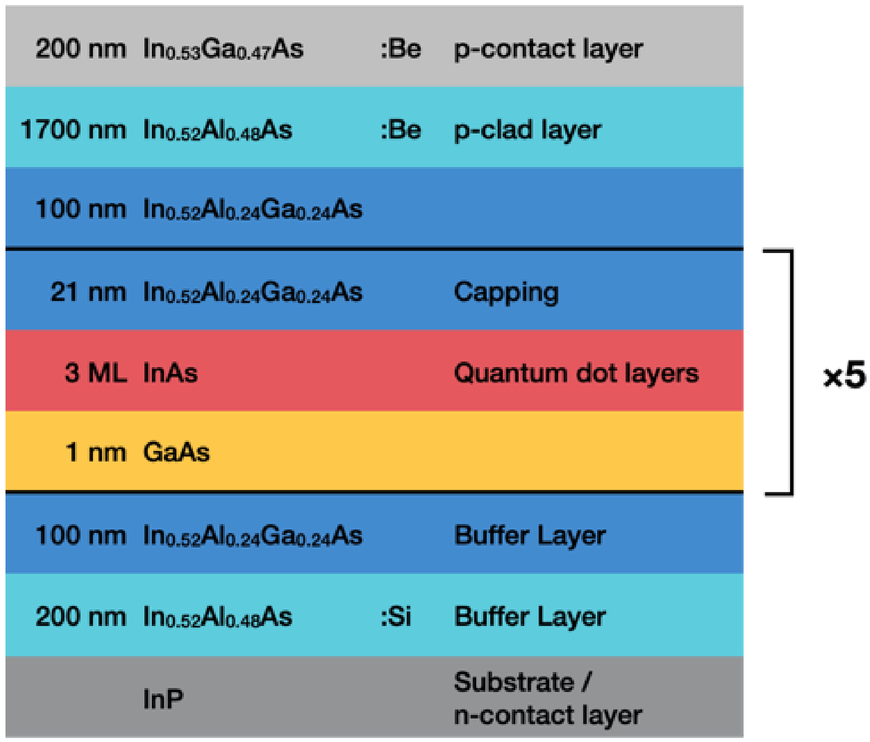
Introduction: Conventional-band (C-band) and long-band (L-band) lasers used in optical communications are prevalent for long-distance communication due to their minimal loss within optical fibers. These lasers play a crucial role in enabling high-speed data transmission over long distances [1, 2]. The potential applications of lasers extend beyond traditional optical communications. Advancements in laser technology have opened new possibilities, such as their use as gain media for silicon photonics and as nonlinear optical components for quantum computing[3, 4]. These emerging fields require lasers with specific properties and capabilities. Quantum dot (QD) lasers have attracted considerable interest in recent years due to their unique characteristics. They exhibit features such as low threshold current density, high-temperature stability, and exceptional emission efficiency [5–7]. These attributes make them promising candidates for various applications. InAs QDs on InP substrates have been extensively researched for C/L-band QD lasers [8–10]. The combination of InAs quantum dots and InP substrates has shown great potential for achieving efficient lasing in the C and L wavelength bands.

However, it is generally standard to concurrently use group V materials, arsenic and phosphorus, in the crystalline growth of C/L-band quantum dot lasers via molecular beam epitaxy. The use of indium materials in fabrication presents several challenges. The production of white phosphorus, which is both spontaneously combustible and toxic, complicates the manufacturing process and poses safety risks. Further, the need for additional phosphorus supply equipment such as cells, pumps, and safety traps increase both cost and process complexity. Moreover, there is a need for precise control over the phosphorus and arsenic mix during crystal growth. These issues can be mitigated by using only Group III-Arsenide (III-As) materials. Without using phosphorus, the manufacturing process becomes safer, simpler, and cost-effective.



However, a new problem arises when phosphides are not used. The problem lies in the ease of migration of indium adatoms due to the high indium content, making it challenging to form InAs QDs. In such cases, quantum dashes that are elongated in the $\left[110\right]$ direction, which promotes indium adatom migration, can be formed. In particular, quantum dash structures [11] have been reported to exhibit luminescent thermalization at high temperatures due to their reduced carrier confinement dimensions compared to QDs. This has a significant impact on laser performance [12, 13]. Several C/L-band lasers employing only As-based growth materials have been reported, however they are either not grown on on-axis InP (001) substrates [14, 15] or utilize additional structures like tunnelling junctions [16]. These factors limit their practicality and applicability.

In this study, we aim to overcome these limitations and explore the growth of a QD laser using only III-arsenide layers on an on-axis InP(001) substrate with a standard QD structure. By focusing on on-axis growth and utilizing only arsenide materials, we can achieve a more practical and efficient laser design. The findings of this study demonstrate successful lasing in the L-band with a threshold current density of 633 A/cm^2. This achievement represents a significant milestone as it sets a new record for the lowest threshold current density in the 1.6 µm-wavelength region for a laser grown on an exact InP(001) substrate.

Experimental method: We utilized a RIBER Compact21 DZ solid source molecular beam epitaxy (MBE) system for sample growth. The Group-III materials Gallium (Ga), Indium (In), and Aluminum (Al) were selected for the experiment, with standard dual filament sources providing these necessary materials. Arsenic dimer (As_2) served as the Group V material throughout the entire growth process. We heated the substrate to a temperature of 530 °C under an Arsenic atmosphere, a step necessary to eliminate the oxide layer.

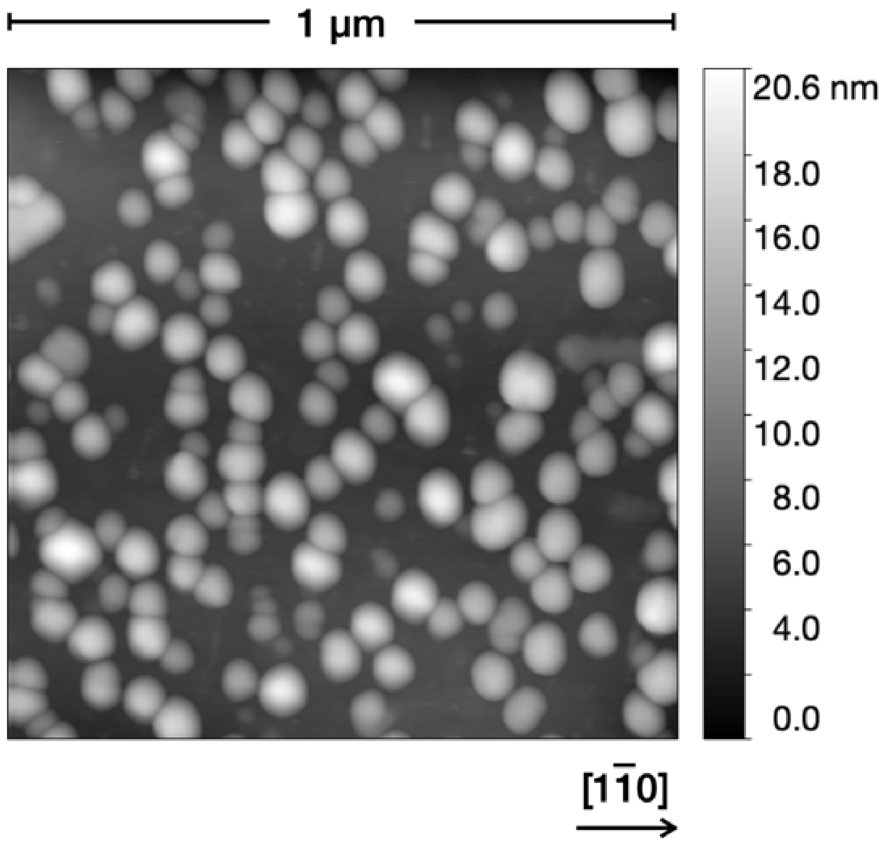
Silicon (Si) and Beryllium (Be) were chosen as n-type and p-type doping materials, respectively.

We grew the epitaxial layer structure on a quarter of a 3-inch n-type InP (001) substrate. Directly on the InP substrate, we grew the first layer, an $In_{0.52}Al_{0.48}As$ lower buffer layer, which notably features a low refractive index (3.20 at 1550 nm). Following the lower clad layer, we then grew a 100-nm thick $In_{0.52}Al_{0.24}Ga_{0.24}As$ waveguide layer. Both layers were lattice-matched to the InP substrate. Subsequently, we grow a 5-layer stacked QD structure, beginning with a 1-nm GaAs layer to promote QD formation, followed by the deposition of 3 monolayers (MLs) of InAs.The InAs QDs were subsequently capped with a 21-nm $In_{0.52}Al_{0.24}Ga_{0.24}As$ spacer layer. After completing the QD layer growth, another 100-nm thick $In_{0.52}Al_{0.24}Ga_{0.24}As$ As layer was grown, followed by a 1700-nm thick $In_{0.52}Al_{0.48}As$ upper clad layer. As the final step in the growth process, we grew a 200-nm thick $In_{0.53}Ga_{0.47}As$ p-type contact layer. The complete epitaxial layer structure can be shown in Fig. 1. We subsequently fabricated the prepared sample into a traditional Fabry-Perot (FP) laser. Both p-type and n-type electrodes utilized AuGeNi/Au as the electrode material. Utilizing a metal mask, we deposited the p-type electrode in a stripe pattern with a width of 100 µm. The n-type electrode was deposited on the backside of the InP substrate. Following these steps, the sample was then cleaved into multiple lengths, ranging from 500 to 3500 µm. We chose not to apply high reflection coating on the laser facets.

Results and discussion: The laser bar samples were characterized through pulsed current injection, with pulse conditions set at a 1 µs signal, 999 µs delay, and 0.1% duty. A Peltier device actively controlled the sample stage temperature. The growth process was evaluated using atomic force microscopy (AFM) to assess surface flatness, QD size, and areal densities. Photoluminescence (PL) was used to characterize the emission spectra.

Figure 2 displays an AFM image of the grown QDs. Due to the limited migration length of indium adatoms on the GaAs thin layer, QD formation exhibited minimal elongation in the $\left[110\right]$ direction. The resulting QDs demonstrated an areal density of 1.61×10^{10} cm^{-2}, an average height of 10 nm, and an average diameter of 56 nm. Figure 3 displays the light-current (L-I) characteristics of a Fabry-Perot (FP) laser at 25 °C, having a cavity length of 3049 µm and a width of 100 µm. The laser's threshold current (I_{th}) and threshold current density (J_{th}) were measured at 1.93 A and 633 A/cm^{2} respectively. The sample displayed multi-mode lasing with a fundamental lasing wavelength of approximately 1620 nm. The device exhibited a series resistance of 3.4 Ω, and a slope efficiency of 1 mW/mA was determined. Figure 4 shows the correlation between the reciprocal of the average threshold current density and the cavity length, demonstrating a reduction in the threshold current density as a result of mirror loss, which increases with the cavity length. The projected threshold current density is 48 A/cm^{2} for an infinite cavity length. Remarkably, both the threshold current density and the projected threshold current density for an infinite cavity length, represent the lowest values ever reported for a 1.6 µm QD laser.

Conclusion: All III-arsenide InAs QD lasers on InP with low threshold current density have been successfully demonstrated. Each epitaxial layer of the QD laser was grown through MBE, and no phosphorus sources were employed. The fabricated laser demonstrates the threshold current density of 633 A/cm^{2}, which is the minimum value for QD lasers in the 1.6 µm-wavelength range. This result suggests a high cost-effectiveness and paved the way toward a large-scale production technology for high-performing C/L/U-band QD lasers.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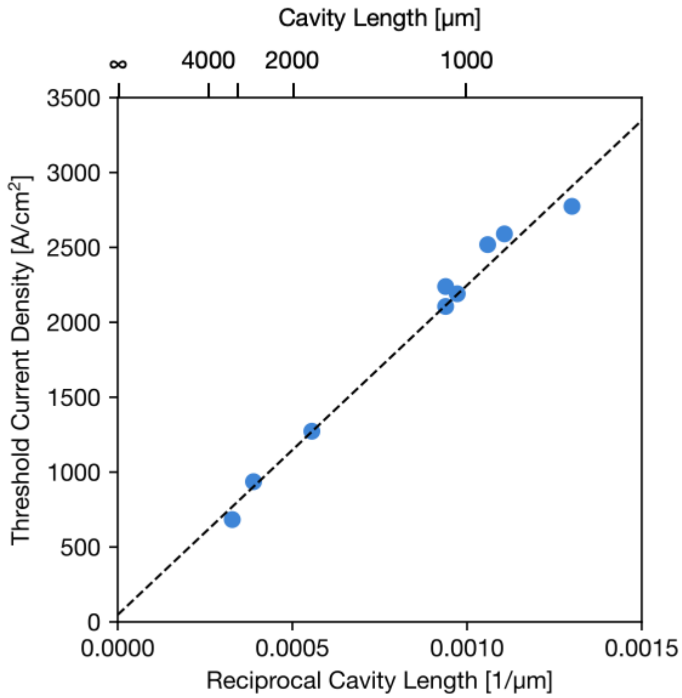
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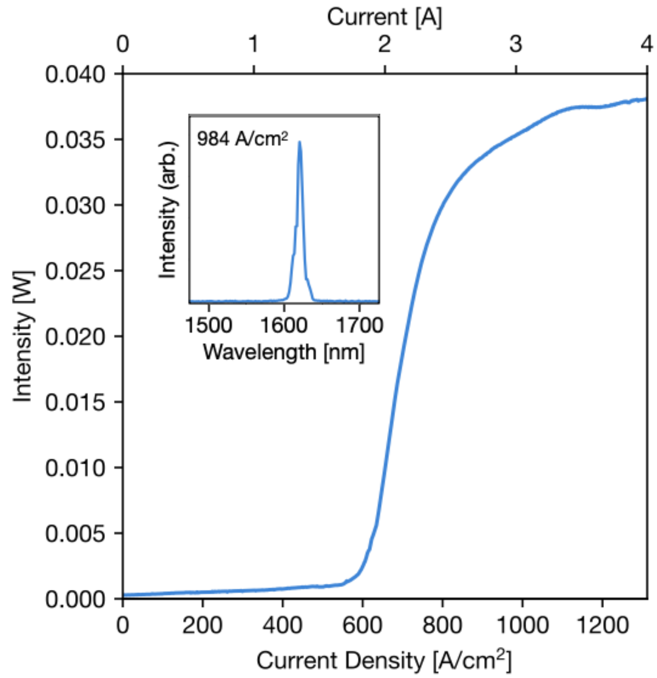

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The data that support the findings of this study are available on request from the corresponding author.

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