SAND2019-15625D

Epitaxial growth & device applications of III-V quantum dots

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U.S. DEPARTMENT OF ENERGY
Office of Science
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Introduction

• Motivation

Quantum dots (QDs) are semiconductor nanostructures that exhibit quantum confinement of carriers in all three spatial dimensions, resulting in atom-like discrete energy states. III-V epitaxial QDs realized by self-assembly have been the subject of intensive research for several years and have proven to be a versatile system with various applications including for:

➢ **Lasers** ➢ **Second-harmonic generation** ➢ **Solar cells etc.**

More recently, their use as **sources of single and entangled photons for quantum applications** has motivated interest in high-quality epitaxial growth of these QDs.

Approach

Based on the specifications of a given application (emission λ, areal density etc.), different categories of QDs can be grown:

• Stranski-Krastanov (S-K) growth

➢ Strain-based 3-dimensional growth. Eg: InAs on GaAs or InP
➢ Lattice mismatch controls shape and size of QD
➢ Emission tunability : ~1-2.5μm (and maybe beyond)

• Submonolayer (SML) QDs

➢ Cycled deposition of strained material – InAs in a GaAs matrix
➢ Emission tunability : 900nm – 1.3μm
➢ Tuned by changing relative thicknesses and periods

Figure 1: Schematic showing difference between S-K (left) and SML (right) QDs

• Liquid droplet etching (LDE)

➢ Formed by etching of substrate to form a nanovoid, followed by filling.
➢ Tuned based on growth conditions and thicknesses. (700—900nm)
➢ Ideal for single photon emitters.

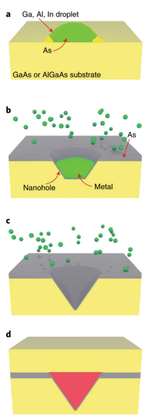


Figure 2: Evolution of LDE method[1]

Results & Discussion

• Tunability

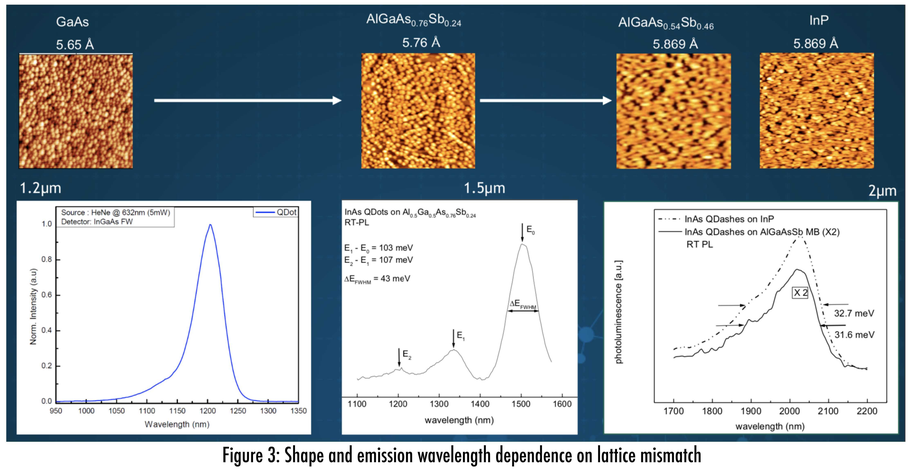


Figure 3: Shape and emission wavelength dependence on lattice mismatch

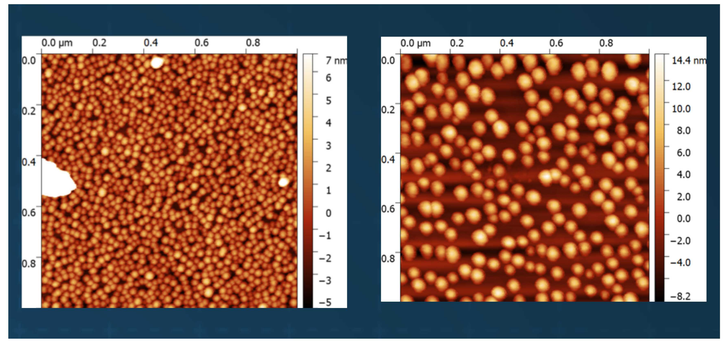
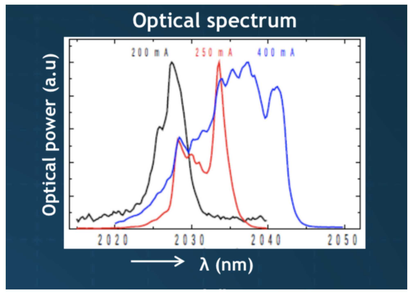
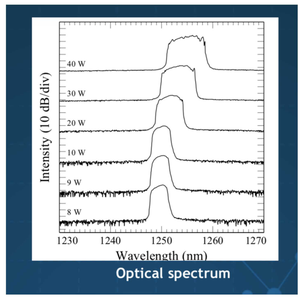


Figure 4: 1 X 1 µm AFM scans showing ability to tune QD density by modifying growth conditions such as temperature, growth rate and III-V ratio

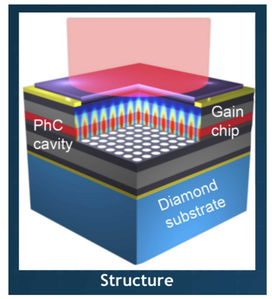
➢ Shape (and emission λ) controlled by tuning lattice mismatch b/w QD material and substrate
➢ Lower lattice mismatch results in elongated QDs – Quantum Dashes
➢ Growth conditions (growth temperature, III:V ratio) optimized for areal density tuning. (especially important for single photon emitters)

• Device results





➢ Low-threshold, high temperature-stable lasers can be realized
➢ Optical spectrum shown for InAs QDash edge emitting lasers at 2μm and InAs QD surface-emitting lasers at 1.25μm



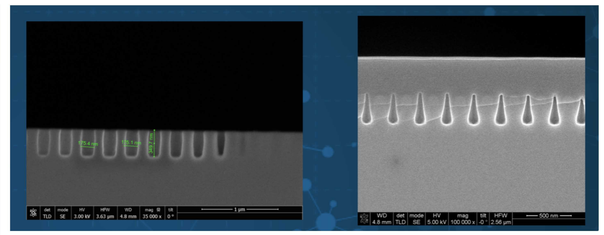
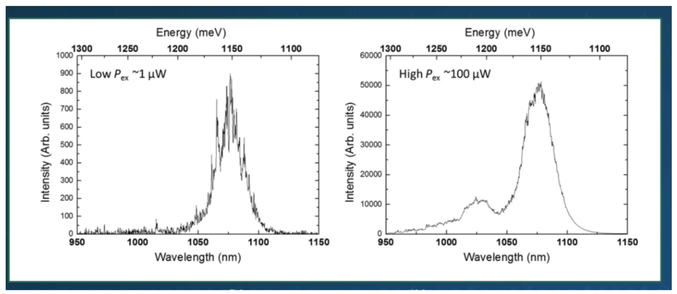


Figure 5: Structure & cross-sectional SEM of PC surface-emitting lasers

➢ QDs can also be integrated with photonic crystal (PC) cavities for PC surface-emitting lasers.
➢ Epitaxial regrowth step necessary to form the PC.



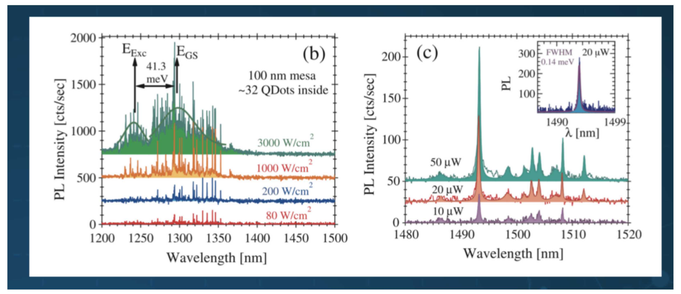


Figure 6: µ-PL: measurements on low-density InAs QDs

➢ At low areal densities, single photon emission can be observed across different wavelengths from QDs.

[1] Gurioli, Massimo, et al. "Droplet epitaxy of semiconductor nanostructures for quantum photonic devices." *Nature materials* (2019):

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This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. DOE's National Nuclear Security Administration under contract DE-NA-0003525. The views expressed in the article do not necessarily represent the views of the U.S. DOE or the United States Government