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Tensile-strained self-assembly: Tunable nanomaterials for infrared optoelectronics and quantum optics

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***Abstract*—Discovered recently, tensile-strained quantum dots are optically active, defect-free nanostructures. Large tensile strains allow us to tailor band structures for applications from tunable infrared emitters to entangled photon sources. I will discuss the history, current state-of-the-art, and future directions of this rapidly expanding research field.**

***Index Terms*—tensile-strain, quantum dots, self-assembly, (111), infrared, optoelectronics, entanglement, quantum optics**

I. Introduction

Since their discovery in the early 1990s [1], III-V semiconductor quantum dots (QDs) have been used as the basis for a wide range of optoelectronic devices, from lasers [2], to single-photon detectors [3]. QDs self-assemble in numerous III-V materials systems [4], [5]; what they all have in common is that the QDs form on (001)-oriented substrates, and the self-assembly process is driven by compressive strain. Attempts to relax either of these constraints and grow QDs on non-(001) surfaces or under tensile strain, typically resulted in highly defective material due to the efficient relief of strain by dislocation nucleation and glide [6], [7].

However, over the last ten years, we have begun to see these restrictions on QD self-assembly relax. Researchers have shown that tensile strain *can* in fact be used to drive QD self-assembly, as long as growth takes place on either a (110)- or a (111)-oriented substrate [7]. In other words, when *both* of the above constraints are lifted simultaneously, the spontaneous formation of dislocation-free QDs can take place. This new ability to achieve QD self-assembly under tensile strain, and on (110) and (111) surfaces, creates an opportunity to synthesize QDs with unique characteristics [8]–[11].

To give some specific examples, we will consider in turn how 1) tensile strain, and 2) the (111) surface orientation, give rise to QD properties particularly well suited to infrared (IR) optoelectronics, and entangled photon emission for quantum communication applications.

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II. Tensile-strained QDs as infrared emitters

In traditional QDs, the compressive strain increases the semiconductor band gap energy, E_g [12]. In addition, quantum confinement within a QD pushes the electron (hole) ground states above (below) the bulk band edge, increasing their energy separation. Since strain and confinement both act the same direction, the net result is a large overall increase in the QD ground state transition energy. A good example is InAs/GaAs(001) QDs, which typically emit at photon energies > 1 eV, a huge increase from bulk InAs where $E_g = 0.35$ eV.

In contrast, tensile strain reduces E_g, and so we now have a tool for red-shifting QD emission relative to the bulk material (Fig. 1(a)) [12]. In addition, because confinement still acts to separate the electron and hole ground states and blue-shift the emission, the resulting "push-pull" mechanism enables precise control of the QD emission energy. The result is that tensile-strained QDs (and quantum dashes) are highly tunable emitters (Fig. 1(a)) [8]–[10], [18], [19]. Strain outweighs confinement in terms of overall impact on the ground state transition energy (Fig. 1(b)), and so we see emission at photon energies below the bulk band gap. Fig. 1(a) shows photoluminescence (PL) from GaAs/$In_{0.52}Al_{0.48}As$(111)A QDs grown with different

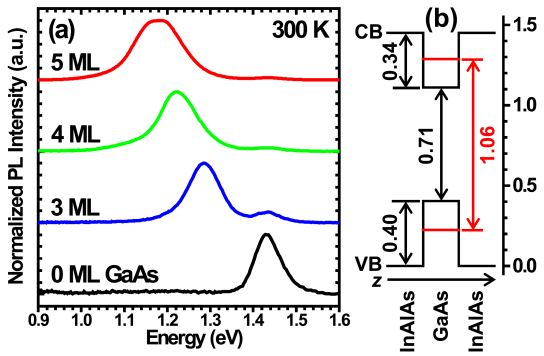

Fig. 1. (a) Room temperature PL from GaAs/$In_{0.52}Al_{0.48}As$(111)A QDs grown with different deposition amounts from 0 ML (i.e., control with no QDs) to 5 ML. (b) Band diagram for GaAs(111)A QDs under 3.8 % biaxial tension. Calculated ground state emission for a 4 ML GaAs QD is in red. All values are in eV. Reprinted from [9], with the permission of AIP Publishing.

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deposition amounts in monolayers (ML). More deposition means larger QDs, and so the emission red-shifts due to quantum size effects. Nevertheless, even the smallest QDs in Fig. 1(a), (i.e., with the largest confinement-related blue-shift), emit at photon energies < 1.3 eV, significantly lower than bulk GaAs ($E_g = 1.42$ eV) revealing tensile strain's impact [9].

Next steps are to adapt this approach for IR optoelectronics by creating tensile-strained QDs from narrower band gap semiconductors. Putting quantum confinement effects to one side, our calculations show that tensile strains of $\sim 4\%$ can lower E_g for most III-V semiconductors by ~ 0.5 eV [8]. These strain-induced changes would push narrow band gap semiconductors (e.g., $E_g < 0.8$ eV) such as AlGaSb or InGaAs down into the mid-IR range ($0.1-0.6$ eV). Even when one reintroduces the blue-shift from quantum confinement, we still expect to observe emission from these narrow E_g tensile-strained QDs in energy ranges that are technologically relevant to various IR applications [13]. Certainly, growing laser structures based on arrays of self-assembled QDs would be a great deal quicker and cheaper than growing equivalent quantum cascade structures.

III. (111) QDs as entangled photon emitters

To grow tensile-strained QDs we are required to change substrate orientation from (001) to either (110) or (111). We should therefore also consider the beneficial properties of QDs grown on these relatively unexplored surfaces. For example, (111)-oriented QDs have long been desirable for quantum optics applications. Compared with (001), the higher symmetry of the (111) surface results in QDs for which the fine-structure splitting (FSS) between the exciton bright states is vanishingly small [15]. FSS ≈ 0 permits the robust quantum entanglement of photon pairs via the biexciton-exciton decay cascade [14], [15]. Entangled photon qubits are central to proposed quantum communication protocols.

Prior to tensile-strained self-assembly the only way to synthesize QDs on (111) surfaces was via droplet epitaxy [16], or growth on pre-patterned substrates [17]. However, this one-step self-assembly process provides a simple way to produce QDs with low FSS. Measurements carried out on individual GaAs(111)A QDs show that > 50 % have FSS ≤ 10 μeV (Fig. 2), suggesting that these QDs represent a scalable route to future entangled photon sources [9].

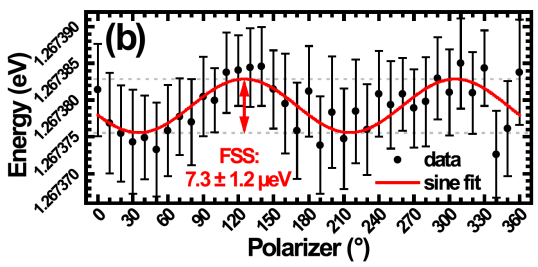

Fig. 2. Peak position of PL emission from an individual GaAs/InAlAs(111)A QD as a function of polarization. A sinusoidal fit reveals an FSS value of 7.3 ± 1.2 μeV. Reprinted from [9], with the permission of AIP Publishing.

IV. Conclusions

Tensile-strained self-assembly enables the controllable synthesis of QDs with narrow band gaps and vanishingly small FSS for IR optoelectronics and quantum optics applications.

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