Semiconductor Quantum Dot Nanostructures and their Roles in the Future of Photonics

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This paper discusses the growth and the properties of semiconductor nanostructures based on self-assembled quantum dots (QDs). These QDs confine electrons or excitons in zero-dimension (0D), similar to an artificial atom or to an artificial molecule in the case of coupled QDs with vertical alignment. They are obtained in a simple step during the epitaxy of strained III-V semiconductors such as InAs on GaAs, or InAs on InP. We will elaborate on the unique optical properties and the physics of self-assembled QDs and their applications, including QD lasers.

1   Introduction

Despite the tough times recently in the telecommunication industry, there is a general feeling that it is approaching a bottom and that innovative devices will enable the next generation of products based on advanced semiconductor and photonic components. Enhanced performance, reduced cost and compact dimensions are a prerequisite for those novel products, and nanostructures could allow the development of such devices. For example, lasers at 1.3 microns on GaAs, widely tunable lasers and/or multi-wavelength sources, semiconductor optical amplifiers, or more defect-robust devices, or devices which can work at higher temperatures, etc. Recently, it has been demonstrated that self-assembled growth can be controlled to systematically and reproducibly fabricate QD structures which have well-defined excited-state transitions, like an artificial atom, and to manipulate their energy levels to tailor the number of confined states and their intersublevel energy-spacing [1]. Moreover, the structural quality of the self-assembled QDs and their compatibility with conventional III-V technology has permitted the demonstration of high performance prototype devices such as semiconductor QD lasers [2]. These developments are very promising for QD devices which can yield novel nanostructures with unique properties due to their atomic-like shell configurations [3]. Other examples, include QD infrared detectors which are sensitive in normal incidence detection due to the geometry of the QDs. Also, optical memories based on coupling of QDs can have large storage density. This paper therefore elaborates on some of the unique optical properties and the physics of self-assembled QDs and their applications.

Mutlilayer stacks of QDs can be grown with good uniformity. For example, Fig. 1 shows the active region of a QD laser with 14 layers where the InAs/GaAs QDs are uni-

form from one layer to the next [4]. This is interesting for improving the gain saturation of QD lasers, but it is also of great interest for coupled QDs. It is possible to engineer the energy levels of such InAs/GaAs QD lasers for emission between ∼900nm to ∼1350nm.
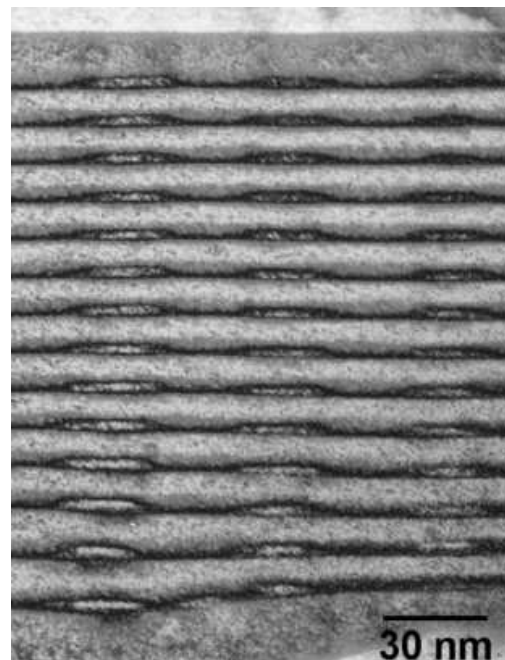

Figure 1. Laser diode with shape-engineered self-aligned QDs. Cross-section TEM of the active region of the laser diode containing a stack of 14 layers of InAs QDs indium-flushed at 5.0nm and separated by 10.0 nm GaAs spacers, McCaffrey *et al.* [4].

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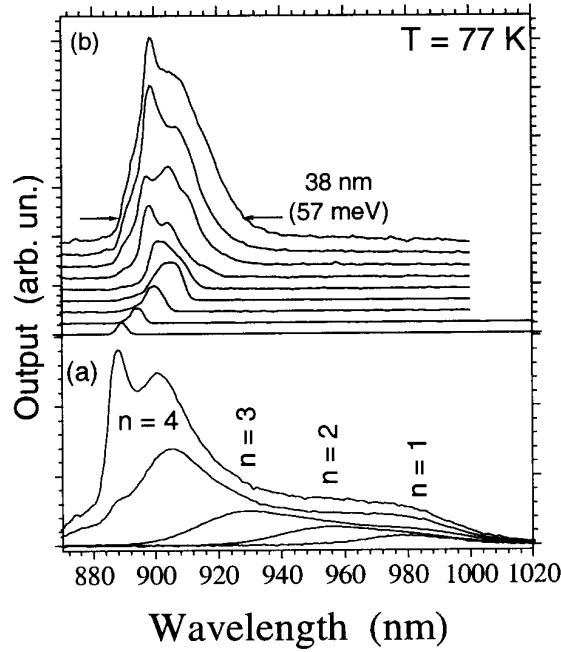†Currently at Bookham Technology, Ottawa, Canada, K2H 8E9

Figure 2. Emission at T = 77 K from the stack of eleven layers with a 500 μm long cavity. (a) State filling spectroscopy with current densities varying from 0.003 A/cm^2 (bottom) to 213 A/cm^2 (lasing threshold) (top). (b) Lasing in an excited states for currents between 230 A/cm^2 (bottom) and 4.0 kA/cm^2 (top).
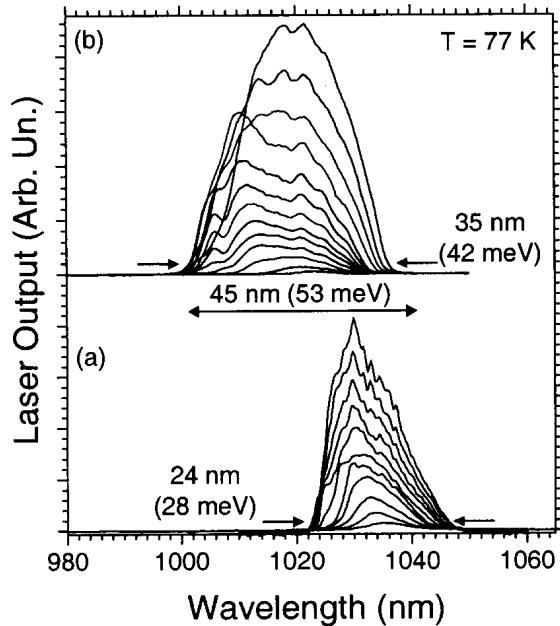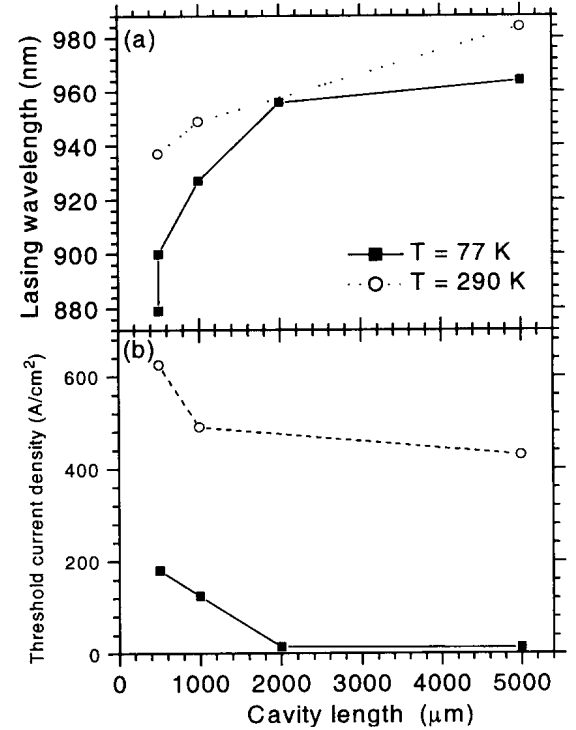

Figure 4. (a) Lasing wavelength, and (b) threshold current density for different laser cavity at T = 77 K and T = 290 K for the sample of Fig. 1.

Figure 3. Lasing at T = 77 K from an InAs/GaAs QD laser with a stack of seven layers; (a) 1300 μm long cavity for current densities between 20 A/cm^2 (bottom) and 120 A/cm^2 (top), and (b) 500 μm long cavity for current densities between 65 A/cm^2 (bottom) and 2.1 kA/cm^2 (top).

The 3-dimensional confinement leads to one of the most important and unique property of the QD lasers: their widely tunable spectrum. The broad QD gain spectrum is applicable to tunable laser sources and to semiconductor optical amplifiers. Indeed, the QD lasers owe their wide gain spectrum to their resemblance to artificial atoms and to the intrinsic property that their density of states can be saturated over a broad range of energy. The simplest demonstration of the QD broad gain is obtained when pumping a Fabry-Perot laser at high current densities, in which case broadband lasing over tens of nanometers can be observed as illustrated in Fig. 2 and Fig. 3. The lasing at various wavelengths can also be obtained by using different laser cavity lengths. This is shown for the near infrared lasers in Fig. 4 which demonstrates tuning over 85nm, obtained by changing the cavity length of broad area Fabry-Perot InAs/GaAs QD lasers. To control the lasing wavelength, a configuration using an external cavity can be used. The output facet of the laser diode needs to be anti-reflection coated and the resonant wavelength is fedback from a dispersive element which can be tuned to select the laser frequency. In nanostructures with 3-dimensional confinement such as self-assembled QDs, it is possible to saturate all the zero-dimensional states from the ground state (s-shell) up to the wetting layer states. This filling of all the QD states has been shown to yield tuning over a wavelength range in excess of a few 100nm depending on the QD energy level engineering.
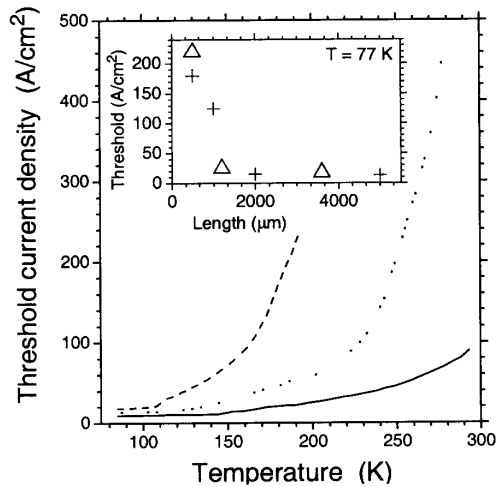
Figure 5. Temperature dependence of the threshold current densities for the three InAs QD samples with long resonant cavities: a stack of seven layers (dash), the stack of eleven layers (dot), and a larger dot density stack of seven layers (solid). In the inset, threshold current density as a function of the cavity length at T = 77 K for the first 2 samples.
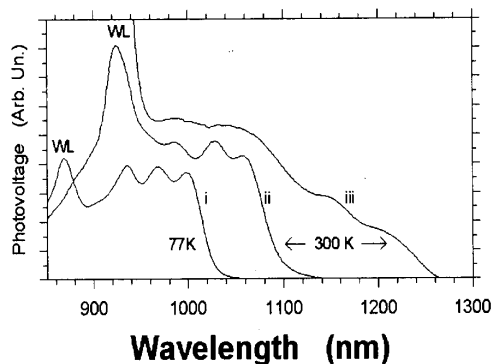

Figure 6. Interband zero-dimensional transitions measured with open circuit photovoltage across QD laser diodes: curve i) is at 77K for a stack of 14 layers indium-flushed at 5.0nm (the laser shown in the TEM in fig. 1), curve ii) is the same laser at 300K, and curve iii) is for a laser diode with a single layer indium-flushed at 8.5nm with a QD ground state close to 1.3 μm at 300K.

As mentioned above, QD lasers can also be grown for $\sim$1.3 micron using the InAs/GaAs material system. Indeed, the 1.3 micron QD lasers have received a lot of attention because of the optoelectronics applications for telecom. In fact 1.3 micron QD lasers are just a different flavor of the near infrared InAs/GaAs QDs using slight variations during the growth of the QDs or cladding materials. Room temperature emission at 1300 nm can be obtained using a distant indium-flush [1] (which leads to more indium segregation) and/or equivalently by using some low concentration InGaAs alloys near the QDs. Alternatively, others have experimented using InGaNAs alloy for the QD formation. Generally, for InAs/GaAs QD lasers, the best performances have been obtained for the longer wavelength emitters.
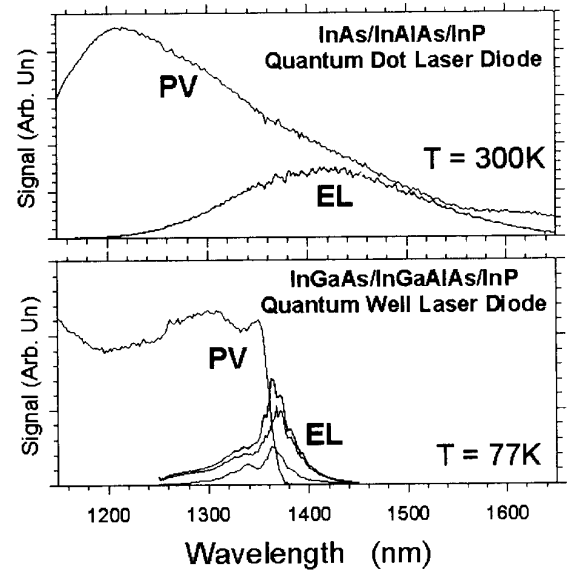

Figure 7. Electroluminescence (EL) and photovoltage (PV) of a QD laser structure (top) and of a control InGaAs/AlInGaAs/InP QW structure grown by MBE.

This is in part because the low energy emission, combined with high barriers, leads to large intersublevel energy spacings and good carrier confinement for separate confinement heterostructures, and consequently a low thermionic emission and a low temperature quenching of the radiative emission. For the QD lasers emitting around 1.3 micron, record current density thresholds have therefore been observed, together with good stability of the characteristic temperatures (T_o). Fig. 5 shows the temperature dependence of the threshold for different QD lasers. The fact that 1.3 micron QD lasers over-performed their quantum well counterparts is exciting, but on the other hand the quantum well technology is a very mature and well anchored for the 1.3 micron emitters and unlikely to be replaced in the near future.

Photovoltage is also a useful tool to characterize the 0D states of the QD laser diodes, as shown in Fig. 6. The photovoltage gives a measure of the absorption when the zero-dimensional density of state is empty of carriers and can be contrasted with the state filling spectroscopy and the lasing spectra to better understand multi-exciton interactions [3, 5].

QD lasers can be obtained in the important 1.5 micron range by using the InAs/InP material system. The substrate is InP while the QDs are still made of strained InAs. The barrier can be made of quaternary InGaAsP or of InGaAlAs as shown in Fig. 7. InAs/InGaAsP/InP QD lasers have been demonstrated with emission at $\sim$1640nm [6]. Larger inhomogeneous broadening has been observed with QDs having non-binary alloys. For example, in the case of red-emitting QDs, systematic studies have shown that it is difficult to obtain QDs with well-resolved excited states, as shown in Fig. 8. For example, the role of the random alloy fluctuations is clarified by growing thin GaAs spacers between the InAs
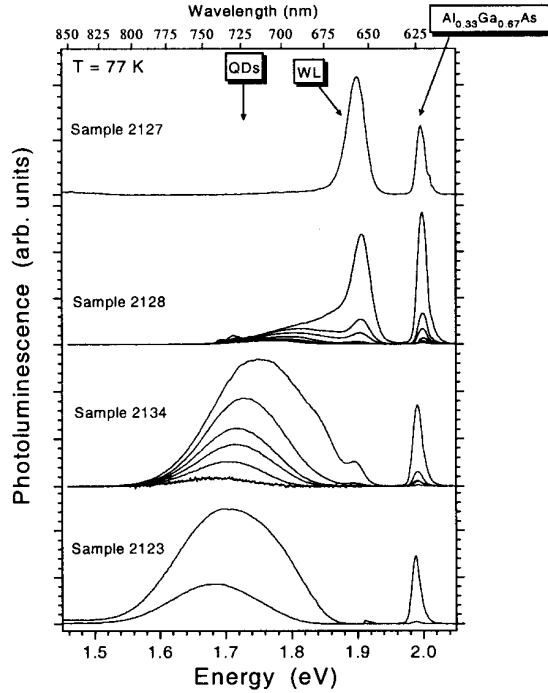
Figure 8. State filling spectroscopy of the AlInAs/AlGaAs samples as a function of excitation intensity. The PL is excited with various intensities up to a few kW/cm^2 for the top curve of each sample. The samples were grown with the equivalent of 0.83nm, 0.86nm, 0.88nm, and 0.90nm of InAlAs from top to bottom respectively.
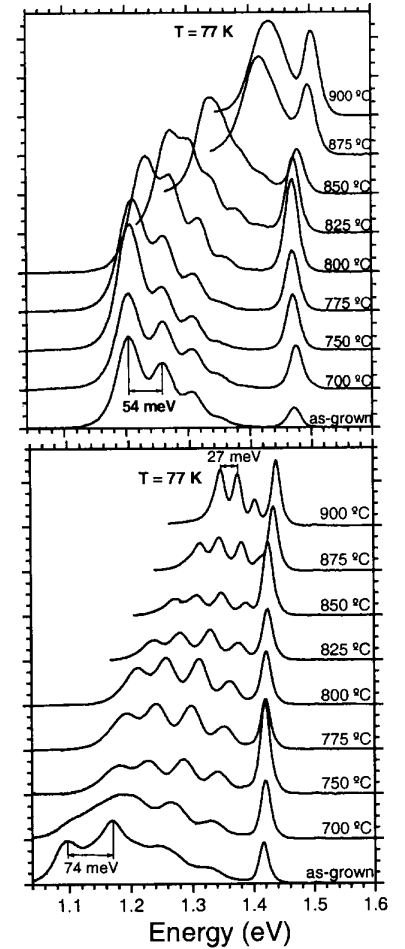

Figure 9. State-filling spectroscopy at 77K for intermixed InAs/GaAs QDs with nearby AlGaAs barriers (top), and without (bottom). The GaAs spacers are 0.6 nm and 5.6 nm for below and above the WL respectively (top). The PL spectra are obtained with the samples which have received a 30s RTA at the indicated temperatures, and exciting with an intensity of $\sim$2 kW/cm^2.

QDs and an AlGaAs cladding and by studying the intermixing [7]. Fig. 9 demonstrates that when the diffusion allows the ternary alloy to be nearby the QDs, the QD excited states are un-resolved. Nevertheless, Fig. 10 demonstrates that the limitations with InAs/GaAs QDs, which have a relatively small confinement energy of the carriers and consequently higher thermionic emission at room temperature, can be circumvented with the use of InAs/GaAs/AlGaAs QDs while preserving a sharp atomic-like shell structure. The emission intensity only decreases by a factor of $\sim$4 between 77K and 300K and well-resolved 0D states are observed at room temperature [7].

2 Conclusion

Semiconductor self-assembled QDs demonstrate unique properties related to their similarity to an artificial atoms. They are compatible with standard III-V technology and have no additional defects. These nanostructures have small sizes that yield large confinement energies, and unique properties such as broadband gain/tunability spectra, low chirp, low temperature sensitivity, narrow homogeneous linewidth, and a gain medium robust to material defects.
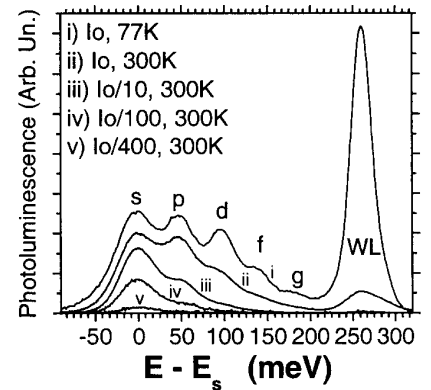

Figure 10. A QD ensemble with both, strong carrier confinement and well-resolved excitonic shells. The intensity of the PL, excited with Io $\sim$ 200 W/cm^2, is compared at 77K and at 300K for InAs/GaAs/AlGaAs QDs with a RTA of 30s at 775 ^{o}C. The energy of the s-shell (E_s) is shifted by $\sim$77 meV between 77K and 300K.

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