Self-assembled quantum dots on GaAs for optoelectronic applications

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Abstract

In the past 20 years the semiconductor laser has become a key device in optical electronics because of its pure output spectrum and high quantum efficiency. As the capabilities of laser diodes have grown, so has the range of applications contemplated for them. The laser performance successes gained using quantum wells in optoelectronic devices can be extended by adopting quantum dot structures. This paper is intended to describe the laser applications of self-assembled quantum dots.

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1. Introduction

Crystal growth and post-growth processing technologies have developed to the extent that it has become possible to fabricate semiconductor structures whose dimensions are comparable with inter-atomic distances in solids. These structures are known as low dimensional structures. The movement of charge carriers in these structures are constrained by potential barriers. This results in the restriction of the degrees of freedom for motion to two, one or even zero. The system becomes two, one or zero dimensional depending on whether the potential barriers confine the carriers in one (layers), two (wires) or three (dots) dimensions, respectively. Carriers exhibit wave-like characteristics and when the layer thickness is comparable with the carrier wavelength the carrier motion is constrained and exciting new physical properties result.

During the last few years much attention has been devoted to the growth and characterization of self-assembled semiconductor quantum dots (QDs). The strong interest in these semiconductor nanostructures is motivated by the possibility to use them as active media in future high-speed electronic and photonic devices.

2. Quantum dots fabrication

A new attractive method of defect free 10 nm scale QD fabrication is the Stranski–Krastanov (SK) growth in lattice-mismatched systems. In the SK growth mode the mismatched epitaxy is initially accommodated by biaxial compression in a layer-by-layer (2D) growth region, traditionally called the wetting layer. After deposition of a few monolayers the strain energy increases and the development of islands (3D) (Fig. 1) becomes more favourable than planar growth [1]. The advantages of this technique of QD fabrication are that no nanotechnology and no further etch or implantation induced process necessary. Since the dots are grown in situ a homogeneous surface morphology is maintained and defect creation is avoided. However, the inherent problem associated with this method is the size non-uniformity and the position uncontrollability of the QD. Controlling the dimension and arrangement of the self-organized 3D structures is thought to be very important for obtaining good properties of the structures.

3. Emission tuning of InAs/GaAs quantum dots

In this Section, I will report on the photoluminescence properties of multiple (InGa)As/(AlGa)As QD layers grown by molecular beam epitaxy under different conditions (i.e. different Al content, number of QD layers,
and different spacer thickness between QD layers. We found that by varying the Al content in the (AlGa)As matrix and/or stacking several QD layers, the room temperature dot luminescence is tuned over a wavelength range from 0.8 to 1.3 μm.

Fig. 2 shows the room temperature QD PL emission for three representatives InAs QD samples. The three samples have different Al content in the Al$_y$Ga$_{1-y}$As matrix surrounding the dots or have different spacing (d) or number (N) of the InAs QD layers. With increasing y, the QD PL band blue-shifts from 1.1 μm (sample A: y = 0, d = 20 nm, N = 3) to 0.8 μm (sample B: y = 0.8, d = 20 nm, N = 3). This blue-shift is due to the deeper carrier confining potential of the dots at higher values of y. In contrast, with decreasing d and/or increasing N, the PL red-shifts from 1.1 μm (sample A: y = 0, d = 20 nm, N = 3) to ~1.3 μm, (sample C: y = 0, d = 1.7 nm, N = 10), evidence for electronic coupling between vertically stacked QDs. Therefore by engineering the carrier potential profile of the dots it is possible to cover a broad energy range for the room temperature light emission of QDs. This is of particular interest for extending the optical emission range of QDs to 1.3 μm, the window for signal transmission through silica fibers.

4. Quantum dot lasers

QDs find significant interest especially for application in laser diodes. It is worth noting that the device, which benefited most from the introduction of quantum wells (QW), is the injection laser. The QW laser reached mass production within very few years because of its low cost, high performance and high reliability. QDs are believed to provide a promising way for a new generation of optical light sources such as injection lasers. QD lasers are expected to have superior properties with respect to conventional QW lasers. Theoretical predictions [2] of the intrinsic properties of QD lasers include higher characteristic temperature $T_0$ of threshold current, higher

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Fig. 1. Scanning tunnelling microscope pictures (100 × 100 nm$^2$) of InAs/GaAs QDs grown by MBE on (100), (311)A and (311)B GaAs substrates [1]. As can be seen, using substrates with different orientation can control the shape of the QDs.

Fig. 2. Room temperature ($T = 290$ K) PL spectra of samples (A) (InAs/GaAs QDs, d = 20 nm), (B) (InAs/Al$_{0.8}$Ga$_{0.2}$As QDs, d = 20 nm) and (C) (vertically stacked InAs/GaAs QDs, d = 1.7 nm and N = 10). The inset sketches the structure for the three samples.
modulation bandwidth, lower threshold currents and narrower linewidth. Fig. 3 shows the development of semiconductor diode lasers based on DHS, QWs and QDs [3]. The lowest current density achieved up to now is 6 A/cm² [4]. Courtesy of D. Bimberg, Technical University of Berlin.

Room temperature 1.3 μm edge-emitting lasers using InGaAs QD structures grown by molecular beam epitaxy on GaAs substrates were demonstrated by several groups using various approaches. These include submonolayer deposition [5], low growth rate [6] and InGaAs overgrowth [7]. Recently it was found [8] that multiple layers (up to 10) of InAs/InGaAs/GaAs QDs considerably enhance the optical gain of QD lasers emitting around 1.3 μm. The differential efficiency as high as 88% has been achieved in these lasers. Emission wavelengths of 1.28 μm, threshold current density of 147 A/cm², differential efficiency of 80%, and characteristic temperature of 150 K have been realized simultaneously in one device (Fig. 4).

5. Conclusions

In this article I have described progress made on QD lasers, which are believed to be ready for practical applications and that their future is extremely promising. The speed of the progress in this area makes it very probable that QD lasers will overcome the performance of QW lasers, in agreement with earlier theoretical predictions.

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References