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Review

The developments of InP-based quantum dot lasers

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HIGHLIGHTS

- The basic properties and growth techniques of InAs/InP QD laser were introduced.
- The recent developments of InP-based QD laser were reviewed.
- The prospects for further progress of InP-based QD lasers were described.

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ABSTRACT

Due to the low density states and high radiative efficiency, quasi-zero-dimensional quantum dot has already exposited major new advances in both fundamental physics and device applications. In this paper we concentrated on the recent developments of the InAs/InP system quantum dot lasers, operating nearby the important fiber communication system of 1.55 μm. In all cases, we stressed the significant progress in the understanding of basic optical and electronic properties to enable the importance steps forward. The developments have been almost covered the important advances for both large ensembles and for individual quantum dots devices, emphasizing the versatility of these systems in opening up a variety of new phenomena. The prospects for further progress directed towards new quantum dot laser for 2–3 μm, stability of single frequency operation with wide tunable range and single photon source are also described.

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1. Introduction

The quasi-zero-dimensional quantum dots (QD) are semiconductor nanostructure with small size in the range of 1–100 nm. Like that of traditional semiconductors, the importance of QD is originated from the fact that its carriers (electron and hole) can be generated by an external stimulus such as voltage or photon flux. One of the main differences between QD and traditional semiconductors is that the peak emission frequencies of QD are very sensitive to both the dot's size and composition. Indeed, the zero-dimensionality of QD carrier states leads to the presence of a limited number of discrete energy levels which are easily saturated. Moreover, Carriers capture is considered to be a random process and usually localized in different dots [1–3]. Those carries may be unable to interact directly, resulting in a system without a global Fermi function and exhibiting an inhomogeneous broadened gain profile [3,4]. Since the QD is successfully fabricated by self-assembled growth mode, QD as active regions of a laser diode has attracted a lot of attentions due to its special structure, which display unique optical and electrical properties that are different in character to those of the corresponding quantum well (QW) lasers and bulk material lasers [5–8]. The self-assembled growth techniques, such as solid-state molecular-beam epitaxy (SSMBE) [9–12], metal organic vapor-phase epitaxy (MOVPE) [13–17], chemical-beam epitaxy (CBE) [18], and gas source molecular-beam epitaxy (GSMBE) [19–22], have been successfully used to grow the QD materials.

QD grown epitaxially using III–V compound semiconductor materials generally has large diameters compared to the Bohr exciton diameter. Such unique properties bring about special performances of QD laser diodes. Up to now, the most studies of III–V compound QD lasers are focused on the InAs/GaAs and InAs/InP system. In the InAs/GaAs system, there has a relative large lattices mismatch between the InAs and GaAs (7%), that means that a small size of InAs QD can be easily deposited on the GaAs-based substrate by Stranski–Krastanow (S–K) growth Mode [23–25]. Good performance of InAs/GaAs QD lasers, providing their emitting wavelength in the fiber telecommunication 1.3 μm, has been obtained by several groups. In order to reach the long haul telecommunication window of 1.55 μm, much efforts have been devoted to further extend the wavelength on GaAs, but at the price of higher threshold current densities and lifetime degradations [26,27]. However, the InAs QD grown on InP-based substrate can be easily performed the wavelength of 1.55 μm because the InAs and InP has smaller lattice mismatch (3.2%). By adjusting the size and the compound of QD on the InP substrate, the lasing spectrum can reach 2 μm and lasers exhibit good performances. Although, the recent developments of QD lasers [28] and quantum dash lasers have been summarized [29].There is no detailed report about the progresses of InP-based QD lasers.

In this paper, we reviewed the recent developments in understanding of some basic properties and improvements of devices' characteristics of quantum dot lasers based on the InP substrates. Besides, from the viewpoints of important applications of singe emission frequency, the developments of external cavity InP-based QD lasers were also introduced. This paper closes with descriptions of some recent developments in the fields of show prospects for further progress directed toward long-wavelength QD lasers and single-dot quantum devices.

2. Basic properties and fabrication techniques of QD

2.1. Basic properties of QD

The fundamental principle behind the operation of nanostructure is the spatial confinement of carriers (or excitons) in the material structure. When the carriers' motion in particular dimension is confined, the energy quantizes. For example, a carrier is confined in an infinitely deep potential well. The probability of finding the particle outside of the barriers is zero, thus the particle wave-function has to vanish at the barrier edges and is thus quantized, which in turn quantizes the particle's momentum and energy [30]. Generally, three basic types of nanostructure can be achieved via spatial confinement in a bulk semiconductor:

(1) Quantum dot is zero-dimensional nanostructure, whose carriers are confined in all three dimensions.
(2) Quantum wire is one-dimensional nanostructure, whose carriers are confined in two dimensions.
(3) Quantum well is two-dimensional nanostructure, whose carriers are confined in only one dimension.

A quantum dot is consisted of hundreds of atoms with a base width of a few tens of nanometers and a height of 4–10 nm. Such zero-dimension size enhances the quantum confinement effect of QD, which greatly localizes its carriers in all three dimensions within a region sufficiently small that the quantum states that are separated by energies of KT or greater, resulting in observable modification of the properties of devices by virtue of its size. Moreover, the special quantum structure makes QD exhibiting a singular energy dependence of the density of states, which are distinctly different than that of traditional quantum well (two-dimension structure) and bulk materials (three-dimension structure), as shown in the Fig. 1 [31,32]. At the same time, self-assembled QD has a naturally non-uniform size distribution, which brings about a broad gain profile. The unique density of states leads to the carrier's rapid filling of the energy levels and consequently allows the wide gain profile to be utilized under the condition of lower operation current and then provide good performances of QD laser, such as lower threshold current density, high quantum efficiency, high characteristics temperature, high wavelength stability and wide wavelength tuneability [33–37].

2.2. Growth techniques of InP-based QD

The technique of QD fabrication that was later applied for current-injection InP-based QD lasers employs the self-organized growth method (Stranski–Krastanow, Volmer–Weber growth mechanisms), which has been demonstrated as effective way to obtain high density of QD [3,4,33–37]. By taking this technique, the QD was usually formed with the strain-induced renormalization of the surface energy of the facets, which means that a layer of a material having a lattice constant different from that of the substrate, after some critical thickness is deposited, may spontaneously transform to an array of three dimensional islands. Before the QD islands formed, some atoms organize themselves in planar form, called the wetting layer (WL). For example, the thickness of WL on the InP substrate is 1–2 monolayer [38]. The lattices of QD are considered to be continuous relaxation in the growth direction when the QD deposited [39], as shown in Fig. 2. So, there does not exist any dislocation after the island finally forms, which has been observed in the Ref. [40]. It is interesting that the size of QD can be turned by adjusting the thickness of InAs layers on InP substrate and then the emission wavelength of 1.53–1.9 μm have been demonstrated [41].

The regular fabrication techniques, etc. the molecular beam epitaxy (MBE), metalorganics vapor phase epitaxy (MOVPE) and Chemical Beam Epitaxy (CBE) are employed to grow InAs/InP QD laser. Each technique has its own merits in fabrication self-assembled QD materials.