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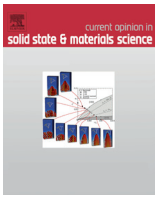

Semiconductor quantum dots

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ABSTRACT

Three-dimensionally confined semiconductor quantum dots have emerged to be a versatile material system with unique physical properties for a wide range of device applications. With the advances in nanotechnology and material growth techniques for both epitaxial and colloidal quantum dots, recently the research has been shifted largely towards quantum dot based devices for practical applications. In this short review, we have tried to assemble a selection of recent advances in the areas of quantum dots for computing and communications, solid state lighting, photovoltaics, and biomedical applications that highlight the state of the art.

1. Introduction

The introduction and development of quantum wells in the 1970's had a rapid and profound impact on compound semiconductor materials and, in particular, diode lasers. In retrospect, it seems obvious that the extension of such one-dimensional quantization (wells) to two-dimensional (wires) and three-dimensional (dots) quantization should have a similar large impact. These are predicted [1–3] to introduce new physical phenomena to diode lasers and other photonic devices. In contrast to quantum wells, however, the synthesis of wire and dot structures is not straightforward. Precision growth of quantum wells in the direction normal to the growth plane in lattice-matched or lightly mismatched heterostructure systems can be obtained fairly easily with modern MOCVD and MBE growth apparatus. Quantum wires and dots require this precision as well but further require some well-controlled process that allows similar precision in one- or two-dimensions in the growth plane. The development of structures, with a suitably high density, or multiple layers, of uniform dots was the primary emphasis in research and development of these structures through the first decade of the 21st century. This has been accomplished using a variety of different approaches including growth on vicinal substrates [4], lithographically patterned structures for etching [5] or selective area epitaxy [6,7], self-assembly for strained layer materials systems [8], colloidal quantum dot solutions [9] and combinations of these [10]. There has also been, of course, incorporation of these various kinds of quantum dots into laser diodes and other, often photonic device structures. Certainly there has also been wide-ranging consideration of the quantum dot materials of choice, including elemental (column IV) semiconductors along with the, perhaps best-studied, III–V compound semiconductors.

In this short review, our goal is to highlight recent advances, particularly in the context of the likely applications for these advances. We address four distinct areas of application. The first is quantum dot lasers for computing and communications, including quantum dot lasers on silicon, quantum dot lasers with extended spectral coverage, and quantum dot lasers for single-photon sources. The second application is quantum dots for solid state lighting. The third is quantum dot solar cells with various approaches to obtaining increased quantum efficiency by means of intermediate band (IB) or multi-exciton generation (MEG) processes. Finally, we consider quantum dots for biomedical applications.

2. Quantum dot lasers for computing and communications

The three-dimensional carrier confinement and localized/discrete carrier states in QDs results in higher efficiency and differential gain with lower threshold current density and high modulation speed in QD lasers. Additionally, linewidth enhancement factor (α-factor), as well as chirp in QD lasers can be much smaller than that in QW lasers, due to a more symmetric gain function in QDs,

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which is also critically important for high speed high performance lasers for optical communications. Finally drastically suppressed thermal spreading of the injected carriers and the relatively large energy separation between the subband levels (ground state and excited states) result in very weak temperature dependence of QD lasing threshold and large characteristic temperatures (T_0). This can lead to athermal operations of QD lasers over a wide temperature ranges [11]. It is also worth mentioning the possibility for fast dynamic response is limited by the strong damping in QD lasers. The comparably low modulation bandwidth of QD lasers is often attributed to the slow charge carrier capture into the QDs, acting as a bottleneck for the laser dynamics. Such limitations are being investigated in more details by a few groups, who proposed enhanced dynamic performance of QD lasers with scattering carrier lifetime engineering [12,13]. Several excellent reviews on QD lasers and related devices and physics were given by several groups [12,14,15]. The growth and QD size non-uniformity control for reduced inhomogeneous linewidth broadening has also been reviewed by Pelucchi et al. [16] Here we will highlight a few major advances of QD lasers for computing and communication systems.

2.1. QD lasers on silicon substrates

One of the roadblocks in silicon (Si) photonics is the reliable and practical light sources on Si substrates. Among various approaches, monolithic or hybrid integration of compound semiconductor materials on Si holds much attention due to its promising towards high performance light sources on Si. Owing to its intrinsic spectral and temperature properties, III–V QD structures are very attractive for Si photonics with potentials of large spectral coverage and uncooled high temperature operation. Impressive lasers with high output power and high operation temperature have been demonstrated by heterogeneous integration of III–V QD lasers on Si substrates through wafer bonding technique [17,18]. Such hybrid approach has led to a wide range of on-chip laser demonstrations based on different types of III–V semiconductor materials, with potentials for wafer reclamation when using smart cut or highly selective etching to perform substrate removal process [19–23].

Monolithic integration is another approach for the integration of III–V compound semiconductors on Si. However the significant material mismatch in both lattice constants and thermal expansion coefficient lead to high density dislocation and other defects generation in the III–V materials. Due to strain engineering and 3D carrier confinement, QDs have good tolerance to defects. Therefore, self-assembled QDs are being pursued actively by many groups since early 80's [15]. Breakthroughs were made over the last few years, with much reduced thread dislocations and high quality QD structures by exploring different types of Si substrates. By using multiple layers of self-organized InGaAs QDs as a very effective dislocation filter, Mi and Bhattacharya et al. reported $In_{0.5}Ga_{0.5}As$ quantum dot lasers with an $Al_{0.07}Ga_{0.93}As$ core waveguide on Si (1 0 0) substrates with 4° offcut towards the [1 1 1] direction [24–26]. A relatively low threshold current density of 900 A/cm^2 under pulsed bias conditions was measured. By modulation doping the laser device with 20 holes per dot, T_0 of 244 K in the temperature range 25–95 °C was achieved.

For optical interconnect and Si photonics applications, it is highly desirable to have Si transparent lasers with longer wavelengths at1.3 and 1.55 μm [28]. The first 1.3 μm QD laser directly grown on Si was reported by Wang et al. [29], where an InAs/InGaAs dot-in-a-well (DWELL) laser structure was directly grown on Si substrate with the use of the optimized GaAs nucleation temperature. Using InAlAs/GaAs strained-layer-superlattice (SLS) dislocation filter layers, Tang and Liu et al. [30] reported 1.3 μm InAs/GaAs QD lasers grown on Si, with a threshold current density of 194 A/cm^2 and output power of ~77 mW. Liu and Bowers et al. [27] demonstrated record performance 1.3 μm InAs QD lasers grown on Si (Fig. 1), with output power exceeding 176 mW and lasing up to 119 °C. The laser was grown on Ge-on-Si substrate, with optimal thermal treatment of the Ge surface along with the GaAs nucleation conditions. The same group also reported high reliability operation of these lasers with over 2700 h of constant current stress at 30 °C [31].

2.2. QD lasers with extended spectral coverages

Taking advantage of the broad spectral coverage, tunable lasers with wide tuning range are also being explored by many groups [32,33]. Recently, Gao et al. [34] reported broadband tunable external cavity lasers based on InAs/InP QDs grown on InP substrates, with a tuning range over 140 nm at 1550 nm spectral band with a maximum output power of 6 mW (Fig. 2).

Another area of focused research in QD lasers is to extend spectral coverage with different material systems. As discussed earlier InGaAs based QDs are largely limited to spectral range from 1 to 1.3 μm. For shorter wavelengths at visible and UV spectral regime, III-Nitride based QD structures are being investigated. As reviewed in Section 5, many interesting results have been reported over the last few years on the demonstrations of QD lasers at red, green, and blue colors.

For longer wavelengths, InP based material systems are being explored for spectral coverage towards 1.55–2 μm [14]. The growth of 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 mm. However, the growth of InAs QDs directly on (1 0 0) InP substrates typically result on reduced dot size control with stronger inhomogeneous linewidth broadening. Many research has been focused on InAs QDs grown on InP (311)B substrate, where high density QDs can be obtained owing to the high density of nucleation points for the QD islands, which also leads to the formation of more symmetric QD in the planar direction [14]. High performance lasers have been reported by a few groups over the last few years. However, challenges remain on the device process problems associated with the mis-oriented substrates, such as mirror cleaving and anisotropic etching.

Technical challenges remain in developing high performance practical and compact lasers at midwave-infrared (MWIR) wavelength range (2–5 μm), where there are important applications in gas sensing, non-invasive medical diagnosis, infrared

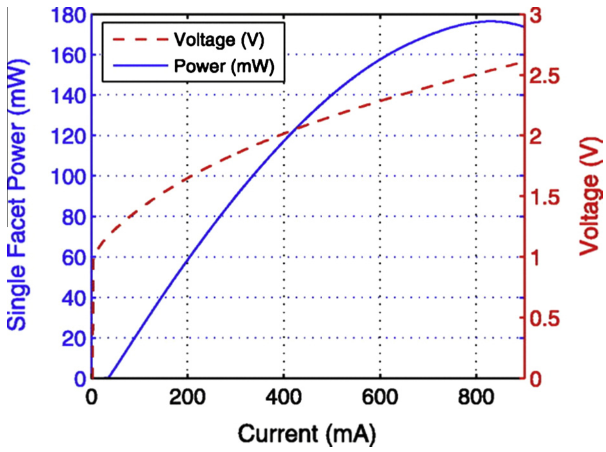

Fig. 1. LIV plot of 1.3 μm QD laser on Si. Threshold is 38 mA with 176 mW of output power at 20 °C [27].

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