Физика и техника полупроводников, 1999, том 33, вып. 9

Quantum dot lasers: the birth and future trends

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(Получена 1 марта 1999 г. Принята к печати 2 марта 1999 г.)

Despite of its early age, laser based on arrays of self-organized quantum dots modified all the basic commandments of the heterostructure laser. Excitonic gain mechanism and discrete energy spectrum in a quantum dot provide principally new ways to control optical properties of the media. Extension of the spectral range using the same substrate makes probable soon appearance of quantum dot lasers on the market.

1. Introduction

The advantage of a discrete energy spectrum and efficient overlap of electron and hole wavefunctions in a quantum dot (QD) [1–4] was recognized already in the early 80-ies. When the first papers [3,4] on the possibility of using QDs as active media of a semiconductor laser with strongly improved and temperature insensitive parameters appeared, many scientists and engineers started searching ways of fabrication of quantum dots and studying their properties. However, more than a decade passed until first lasers based on self-organized QDs have been fabricated in 1993 [5] and were proven to demonstrate the predicted properties [6].

2. Ways to fabricate quantum dots

Currently the most promising way to fabricate QDs is based on the effect of spontaneous nanoislanding during heteroepitaxial growth. Flat (2D) nanoislands are usually formed by submonolayer deposition and the driving force relates to the surface stress discontinuity at the island edges. The elastic relaxation of the surface stress along the island boundary makes formation of uniform in size nanoislands energetically favorable [7]. After overgrowth 2D islands represent ultrathin nanoscale "pan-cakes" inserted in a wide gap matrix. The localization energy of carriers and excitons in these islands is relatively small, except of materials with large electron and hole masses are used (II–VI materials, group-III nitrides). In view of the small average thickness of the insertion, a possibility to stack strained 2D islands by keeping the average strain in the epilayer low exists. Arrays of 2D islands usually provide much narrower absorption or gain peaks.

In the case of 3D islands [7] the driving force relates to the elastic relaxation of the volume strain of the island formed on a lattice mismatched substrate. Possibility of stable with respect to ripening 3D islands appears if the total surface energy of the island is smaller than the surface energy of the corresponding area of the wetting layer occupied by it. The latter is possible if the strain-induced renormalization of the surface energy of the facets is taken into account [8].

Oscillator strength in a small QD is not a function of the QD volume. Thus, dense arrays of very small QDs ($10^{12}\,\mathrm{cm}^{-2}$) provide much higher modal gain, as compared to a more dilute array of larger QDs (typically about $10^{10}-10^{11}\,\mathrm{cm}^{-2}$). On the other hand larger QDs can provide much higher localization energy. This gives some flexibility in constructing of the device. In case when one is interested to keep hight maximum absorption or gain values, 2D islands are preferable. High temperature stability of the threshold current and a maximum long-wavelength shift of the emission (e.g. 1.3 or 1.5 μm range using GaAs substrates) are realized for 3D islands.

Dense arrays of QDs can demonstrate lateral ordering due to their interaction via the strained substrate [8]. Stacked 3D QD deposition demonstrate vertically-correlated growth [9,10]. 2D islands demonstrate either correlated or anticorrelated growth depending on the relative thickness of the spacer layer [11].

Several other promising ways to fabricate QDs using self-organization phenomena exist (see e.g. [12] and references therein):

– spontaneous quasiperiodic faceting of crystal surfaces and heteroepitaxial growth of faceted surfaces;

– spontaneous phase separation in semiconductor alloys during growth or slow cooling;

– spontaneous alloy decomposition upon high-temperature annealing.

3. Edge emitting and vertical cavity quantum dot lasers

Evident progress in using of QDs is achieved in the area of semiconductor lasers. Two basic device geometries have been applied. In one case, the light propagates along the plane with QDs, and the resonator represents conventional Fabri–Perot cavity with nutural cleavages as mirrors (see Fig. 1, on the right). In the other case, the light is emitted perpendicular to this plane (see Fig. 1, on the left), while the cavity is confined in vertical direction by multilayer stacks of layers forming distributed bragg reflectors.

The first approach allows fabrication of high power lasers utilizing advantages of ultralow threshold current density due to QDs, possible preventing of dislocation growth and suppression of the laser mirror overheating by nonradiative surface recombination due to localization of carriers in QDs [13]. In the second approach lasers

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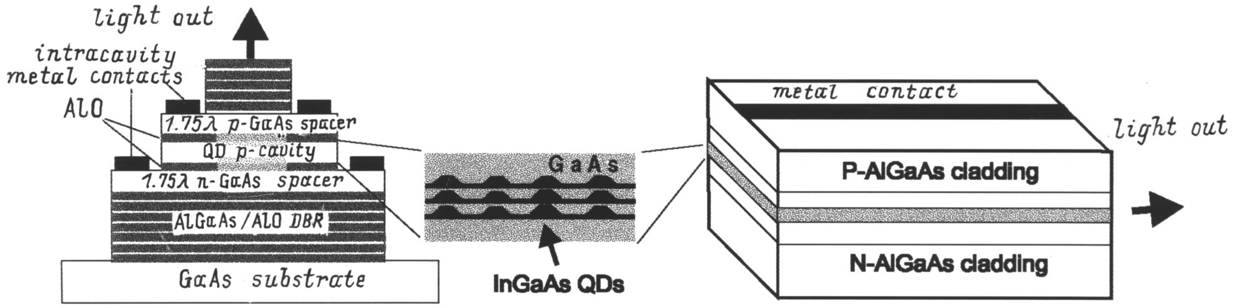

Figure 1. QDs are used as active media of semiconductor heterostructure lasers in edge-emitting (right) and vertical cavity (left) geometry.

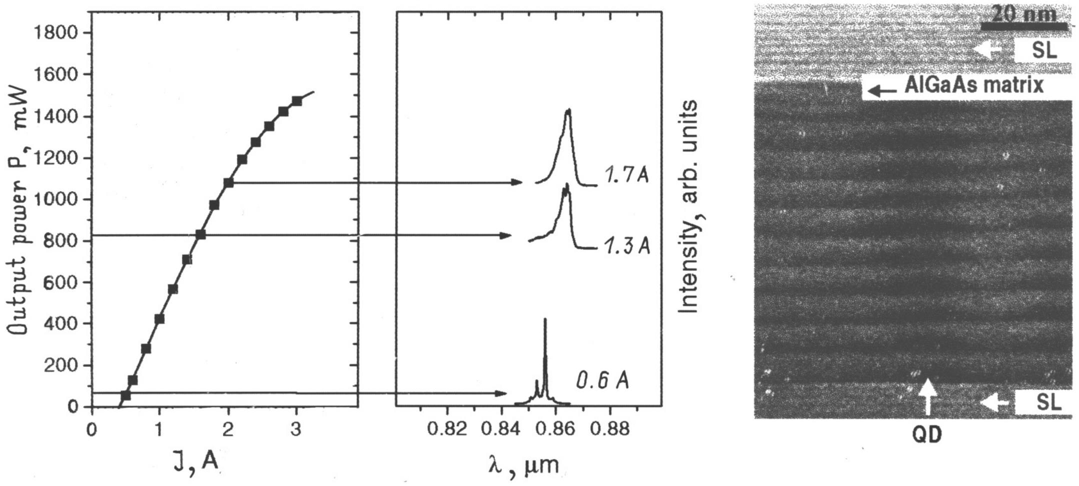

Figure 2. High-power operation of edge-emitting InAs/AlGaAs QD laser (left). Transmission electron microscopy image of the active region of the high power QD laser (right). Stripe length 850 μm, width 100 μm, waveguide region 0.3 μm.

with ultralow total currents can be fabricated, and, even more exciting, lasers based on single QD can be potentially realized.

The important events in the QD laser field can be briefly listed here.

– Photopumped QD laser has been first realized by Ledentsov et al. in 1993 at Abraham Ioffe Institute [5].

– First QD injection laser has been fabricated in 1994 by a joint from Technical University of Berlin and Abraham Ioffe Institute. Lasing via the QD ground state and the temperature insensitive threshold current have been demonstrated [6].

– Room temperature (RT) operation via quantum dots has been demonstrated [13–17].

– Ultrahigh material and differential gain in QD lasers have been manifested [18].

– RT lasing with 60 A/cm^2 has been realized [19].

– Continuous wave RT high power operation of a QD laser (1.5 W [20]) was realized (see Fig. 2). For copper heat sink and waveguide layer thickness of about 0.3 μm these structures show comparable results to the state of the art quantum well (QW) devices.

– Low threshold InAs QD laser on InP substrate [21] emitting at $1.84 \div 1.9\,\mu$m has been fabricated.

– Significant progress in theoretical understanding of QD lasers with realistic parameters has been achieved [22,23].

– QD lasers operating in the visible spectral range has been demonstrated [24].

– Vertical-cavity surface emitting lasers (VCSELs) based on QDs with good properties have been demonstrated by Huffaker at al. [25].

– The joint team from Abraham Ioffe Institute, Air Force Institute of Technology, Ohio, USA and Technical Universtiy of Berlin demonstrated a QD vertical-cavity laser with parameters which fit to the best values for devices of similar geometry based on QWs [26] (see Fig. 3).

– 1.31 μm lasing at room temperature with a threshold current density of 240 A/cm^2 is demonstrated for the device based on InGaAs QDs in a GaAs matrix [27].

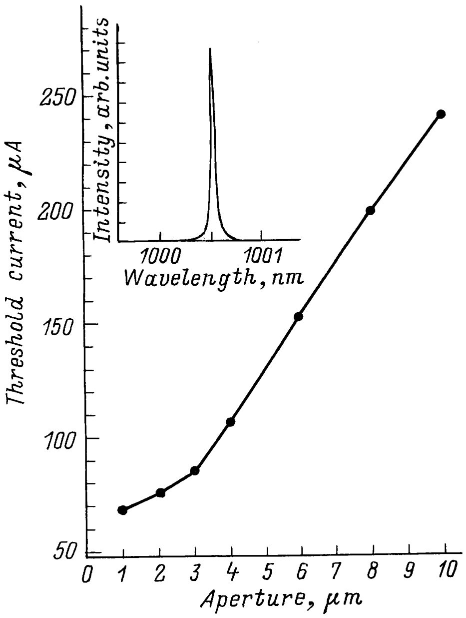

Figure 3. Threshold current (J_{th}) of the QD VCSEL. The emission spectrum at $1.3J_{\text{th}}$ is shown in the insert. Quantum efficiency $\eta = 16\%$ at 10 μm.

Generally, the basic parameters of edge emitting and vertical-cavity QD lasers approached those for QW devices, while the QD laser story is only starting.

4. Unexpected results

4.1. Far-infrared emission in quantum dot lasers

In ultrathin layers, or QWs, there exists a continuum of states at any energy above the subband energy, as the in-plane motion of charge carriers is not limited. If the carrier is excited to the second subband, it relaxes to the first subband via emission of a descrete quanta of energy — an optical (LO) phonon. Due to the continuum nature of electron states in a QW, there always exist states in the first subband to which electron can scatter within 1 ps. Contrary, in QDs the relaxation time to the ground sublevel takes typically $10 \div 40$ ps. The electron needs to emit a combination of different phonons to match the energy difference. This slowering increases the relative importance of the competing relaxation mechanism via emission of far-infrared (FIR) photons [28].

In [28] the FIR emission was observed in QW and QD lasers. The intensity of the FIR spontaneous emission was about one order of magnitude higher in the QD case. Moreover, the FIR emission in QDs has a threshold character as it requires fast Much higher intensity of the FIR emission in the QD case, hopefully, will make it possible to create a new generation of FIR lasers.

4.2. Extension of the spectral range of GaAs-based devices to 1.8 μm

QDs allows a possibility to cover strategically important spectral ranges of 1.3 and 1.55 μm using GaAs substrates. This is particularly important for VCSELs where high quality monolithic AlAs–GaAs Bragg reflectors and developed oxide technology are available only on GaAs substrates. Recently it was discovered that associates of InAs QDs formed at low substrate temperatures [29] emit light at wavelengths up to 1.8 μm at 300 K.

4.3. Resonant waveguides

The experimentally measured absorption coefficient for structures with stacked CdSe QDs in a ZnSe matrix in the direction perpendicular to the planes with nanoislands approaches $\alpha = 10^5\,\text{cm}^{-1}$ [30]. High absorption coefficients and lack of exciton screening in dense arrays of QDs result in ultrahigh QD exciton (or, even higher, biexciton) gain values under generation of nonequilibrium carriers [31].

Resonant waveguides are based on the effect of resonant enhancement of the refractive index (n) along the contour of the absorption (or gain) curve. To have a significant impact on the waveguiding properties of the media the absorption peak is to be strong enough ($\Delta n \sim 0.5$ for $\alpha \sim 10^5\,\text{cm}^{-1}$). For resonant waveguiding it is not necessary to have external cladding of the active region with QDs by layers with significantly lower refractive indices. Practically, it means that lasers can be created in materials having no suitable lattice-matched heterocouple with lower refractive index.

4.4. Self-adjusted cavities

In VCSELs the effect of strong resonant modulation of the refractive index serves for self-adjustment of the cavity mode and lasing spectrum. As the material gain of a single QD reaches ultrahigh values due to δ-function-like density of states and negligible homogeneous broadening, even single quantum dots lasing may become possible [32].

4.5. Vertical cavity lasers without Bragg reflectors and cavity

A highly reflective Bragg mirrors on both sides of the cavity are necessary for QW VCSELs, as relatively small maximum gain in these structures (about $10^3\,\text{cm}^{-1}$ [4]) require low external losses of the device. However, if the maximum gain can be made high enough, no necessity in highly reflective Bragg mirrors exists. For gain values exceeding $10^5\,\text{cm}^{-1}$ and active layer thickness of 200 nm the facet (or mirror) reflectivity of the order of 30% is enough to achieve vertical lasing. Due to the low finesse of the cavity and the self-adjustment effect no strict necessity in fitting of the cavity made and the gain spectrum exists. This effect was demonstrated for 20-times stacked CdSe submonolayer QD insertions in a ZnMgSSe matrix [33] grown on GaAs substrate.

4.6. Quantum dot composites

The gain of the array of QDs is not defined by a simple sum of gains of single QDs. Interaction of electromagnetic fields of anisotropic QDs or anisotropic QD lattices makes the splitting of the TE and TM modes for the same QD exciton transition inavoidable. This effect can result in splitting as large as several tens of meV, as was predicted theoretically and is proven experimentally [33]. Maximum gain of the QD ansemble is also a strong function of the relative arrangement of QDs [33].

4.7. So called "quantum well" lasers

Most of recent industrial QW lasers are based on thin layers of alloys used as active regions. It becames clear now, that these layers, in most cases, exhibit quasiperiodic nanoscale compositional modulations creating in many cases dense arrays of quantum wire- or QD-like structures [12]. By using the same average alloy composition the luminescence peak energy can be tuned by several hundreds meV by tuning the growth conditions [34]. Careful evaluation of the impact of such effects on lasing characteristics of modern lasers is nesessary to clear up the role of sefl-organized QDs or quantum wires in this case.

5. Conclusion

QDs [35] modified all the basic commandments of the double heterostructure (DHS) laser [36,37].

DHS, DHS QW	QD
— lattice matching	undesirable
— material gain	orders of magnitude higher
— exciton screening	is not important
— homogeneous broadening at RT	is small
— cladding with low *n* layers	is not necessary
— VCSEL: Bragg reflectors and cavity	are not necessary
— lasing in optical and near IR range	and simultaneous FIR emission
— one family ($A^{III}B^{V}$–$A^{III}B^{V}$, . . .)	is not necessary (InAs/Si QDs)
— limited wavelength range on GaAs	is extended to 1.8 μm

It appeared that the QD laser seems to be a completely new device with properties which can remarkably expand our possibilities in many application, rather than simply a laser with some parameters improved with respect to the DHS or DHS QW laser [3,4].

Original results mentioned in this work became possible due to cooperation with my colleagues at A.F. Ioffe Physico-Technical Institute, St.Petersburg, Institut für Festkörperphysik, Technische Universität Berlin, Technical University of St.Petersburg, Max-Planck-Institut für Mikrostrukturphysik, Halle, and the Institute for Analytical Instrumentation in St.Petersburg. We acknowledge support from the Russian Foundation of Basic Research, Volkswagen Foundation, INTAS, and Deutsche Forschungsgemeinschaft. The author is personally grateful to the Alexander von Humboldt Foundation.

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