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Philipp Ridha, Lianhe Li, Andrea Fiore, Gilles Patriarche, Meletios Mexis, and Peter M. Smowton

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Polarization dependence study of electroluminescence and absorption from InAs/GaAs columnar quantum dots

Philipp Ridha,[a)] Lianhe Li, and Andrea Fiore
Ecole Polytechnique Federale de Lausanne (EPFL), Institute of Photonics and Quantum Electronics, 1015 Lausanne, Switzerland

Gilles Patriarche
LPN/CNRS, Route de Nozay, 91460 Marcoussis, France

Meletios Mexis and Peter M. Smowton
Cardiff University, The Parade, Cardiff, CF24 3AA, United Kingdom

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Semiconductor optical amplifiers based on InGaAs columnar quantum dots (CQDs) with different numbers of superlattice periods were fabricated and tested. The polarization dependence of the electroluminescence (EL) and absorption of such CQDs structures were measured. Compared to standard QDs a large improvement in the ratio of transverse-magnetic (TM) and -electric (TE) integrated EL was obtained in CQDs, depending on the number of stacked GaAs/InAs superlattice periods, which can be attributed to the more symmetric shape of CQDs. TM and TE resolved photovoltage absorption spectroscopy confirmed this improvement. A small spectral separation between TE- and TM-EL peaks has been observed showing that heavy and light holelike states are energetically close in these QDs. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2811720]

Quantum dots (QDs) have a potential for application in semiconductor optical amplifiers (SOAs) due to their high saturation power related to the low differential gain, fast gain recovery and wide gain spectrum compared to quantum wells (QWs).[1–3] However, polarization-independence is also needed for in-line amplifier applications. Due to their flat shape and quasibiaxial compressive strain, self-assembled quantum dots have a valence-band ground state of the heavy-hole (hh) type, which does not couple to light polarized along the growth axis, i.e., transverse-magnetic (TM) mode in a guided-wave configuration. A hope exists, however, that both the shape of the confinement potential and the strain distribution can be changed by varying the QD aspect ratio, e.g., by changing the QD growth conditions,[4–6] or using a capping layer,[7] or close-stacking of several QDs.[8] In particular, depositing a short-period GaAs/InAs superlattice (SL) on top of a seed QD layer results in the formation of *columnar* quantum dots (CQDs) with high aspect ratio.[4–6,9–11] The polarization properties of photoluminescence (PL) from the cleaved edge have been investigated for CQDs (Refs. 4, 12, and 13) and evidence of net TM gain under optical pumping has been reported very recently,[12] but no lasing. However, so far, no polarization studies under electrical pumping have been carried out. Electroluminescence (EL) is a more consistent technique for the polarization analysis of edge-emitted luminescence, as stray emission from the surface is blocked by the metal contact. We have measured the polarization-resolved edge-emitted electroluminescence in a series of CQD SOA structures leading to interesting insights of QD polarization properties as a function of the QD aspect ratio. Additionally, we report an investigation of the CQD polarization-resolved absorption spectra by photovoltage spectroscopy, which further confirms our conclusions. The active region material of our QD SOAs is based on either standard Stranski-Krastanov (SK) growth of QDs or CQDs. In the latter case, on top of a first layer of *seed* QDs, a GaAs/InAs SL is grown. The InAs thickness deposited in each cycle is lower than the critical thickness, and the GaAs spacer is only few monolayers thick, so that effectively a single nanostructure is formed after the cycled InAs/GaAs SL deposition. The growth sequence of CQDs with a growth rate 0.1 ML/s is as follows: y MLs InAs+$N\times$(3 MLs GaAs/x MLs InAs)/GaAs. Growth optimization was described in detail elsewhere.[6] Growth conditions resulting in optimized room-temperature PL were used in the present work, $y=1.8$ MLs, $x=0.7$ MLs, and $N=10-35$. The formation of CQDs was confirmed by $g=\langle 002\rangle$ dark-field cross-sectional transmission electron microscopy (TEM) images (see Fig. 1), which provide information on the chemical contrast.[14] Indium-rich islands with 35% of indium content are observed, much taller than usual

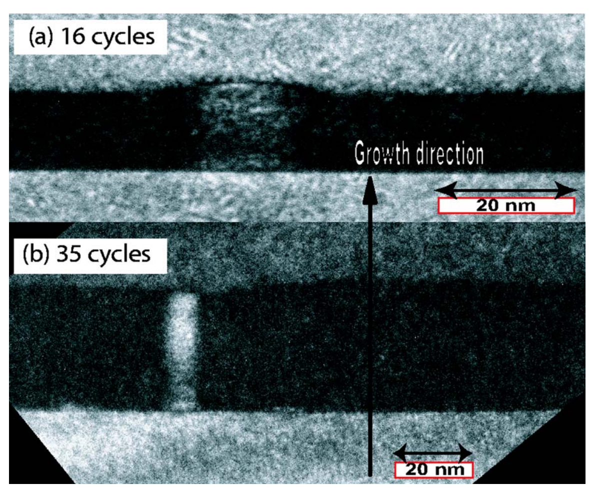

FIG. 1. (Color online) TEM images of columnar QDs with (a) 16- and (b) 35-repetition cycles of InAs/GaAs superlattice.

[a)]Electronic mail: philipp.ridha@epfl.ch

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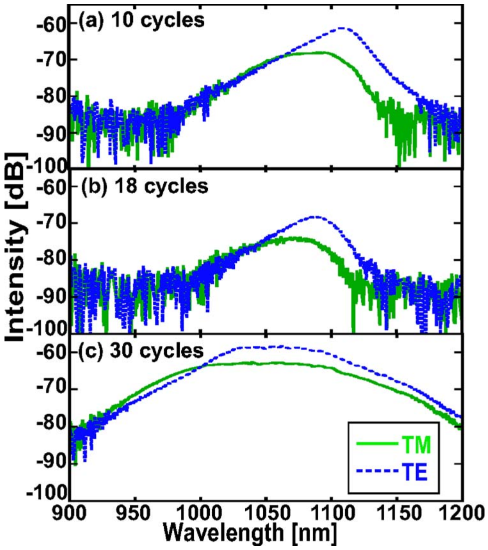

FIG. 2. (Color online) Edge-emitted electroluminescence spectrum of columnar QDs with (a) 10-, (b) 18-, and (c) 30-repetition cycles of InAs/GaAs superlattice measured at a current density of 200 A/cm^2.

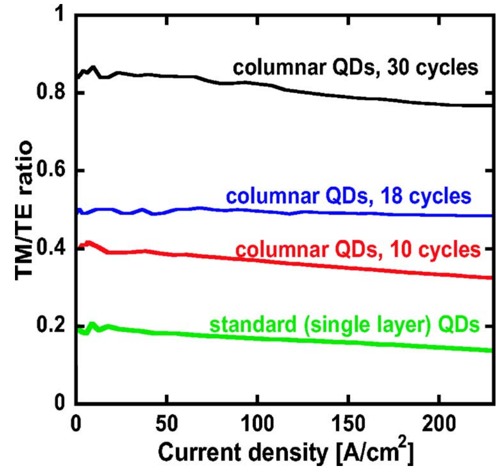

FIG. 3. (Color online) TM/TE ratio of integrated intensities for SOAs with different active regions: standard 40-nm-spaced and columnar QDs (10, 18, and 30 cycles).

Stranski-Krastanov QDs. They are embedded in a QW structure (dark region) with 16% of indium. CQDs are formed with (a) cubic or (b) nanorodlike shapes depending on the number of InAs/GaAs SL periods. The height is directly controlled by the number of SL periods, while the diameter was observed to vary between 10 and 20 nm depending on growth conditions. It should be noted that these QDs represent a very peculiar type of nanostructure, as compared to standard SK QDs. They may have interesting properties, besides polarization dependence, for laser applications. The active region based on CQDs has been embedded between two AlGaAs cladding layers and processed into ridge waveguide laser structures of 2 mm length and 20–120 μm width. The edge-emitted EL was measured from SOA structures incorporating one to five layers of CQDs, each based on 10, 18, or 30 InAs/GaAs cycles. The 10- and 18-cycled CQD structures have 20 nm diameter and were grown under similar conditions as 16-cycled CQD shown in Fig. 1(a). On the other hand, the 30-cycled CQDs have 10 nm diameter and were grown under equivalent growth conditions as 35-cycled CQD [Fig. 1(b)] structure. The estimated aspect ratio is 0.63, 1.13, and 3.51 for 10-, 18-, or 30-cycle CQDs, respectively. We measured the polarization-resolved and integrated EL at room temperature using a collimating lens, a polarization filter, a focussing lens, and a Germanium photodiode connected to a lock-in amplifier. The linear polarizer has an extinction ratio $>10^5$ in the 850–1600 nm wavelength range. With the same experimental setup, by coupling the signal after the second lens into a fiber, the edge-emitted EL spectrum was measured by a optical spectrum analyzer. We note that due to the metal contacts on top of the device, luminescence coming from the sample surface is not collected, and only edge-emitted luminescence is measured. From polarization-resolved EL TE and TM emission spectra [see Fig. 2(a)] 10- and (b) 18-cycles CQDs show a spectral separation between TE- and TM-EL peaks of $\Delta E \sim 20$ meV. On the other hand, while several QD bound states are likely to contribute to the measured spectra, no clear spectral separation between TE and TM emission is observed in the 30-cycles sample [Fig. 2(c)]. The smaller energy separation of TE and TM emissions in CQDs with increased aspect ratio is the consequence of the more favorable profile of the confinement potential and strain distribution. Indeed, while heavy-hole and light-hole (lh) bands are mixed by the three-dimensional confinement, the TM-polarized dipole is associated to states with large lh component (we refer to these states as "lh-like" in the following). In an (ideal) InGaAs column-shaped insertion in GaAs, the strain evolves from compressive to tensile as the height is increased. Combined with the effect of anisotropic quantum confinement, this lowers the energy of hole states with large lh component and would result in a lh-like ground valence-band state for aspect ratios >1, in InGaAs columns fully embedded in GaAs. In order to facilitate a quantitative comparison between the different numbers of InAs/GaAs SL repetition cycles, Fig. 3 presents the ratio of TM and TE integrated electroluminescence intensities from SOAs incorporating columnar (10, 18, and 30 cycles) and standard 40 nm spaced QDs grown by continuously depositing 2.64 ML of InAs. A clear improvement in the TM/TE ratio is observed with increasing number of cycles. Indeed, as the hh- and lh-like states come closer in energy, they are more equally populated even at low current.

With edge-photovoltage spectroscopy[15,16] we measured the polarization-dependent absorption of monochromatic light incident on the cleaved facet of the CQD samples. Varying the wavelength of the incident light by using a lamp and a monochromator, the energy levels in the QW and QD regions of the sample can be measured from the resulting absorption spectra for hh- and lh-like transitions. For standard QDs the photovoltage absorption spectrum [Fig. 4(a)] reveals a TM absorption much weaker than TE at the ground-state peak wavelength of 1280 nm. A lower difference between the two polarizations is observed at higher energies corresponding to excited states. The absorption spectra of CQDs [Fig. 4(b)] clearly shows a decreasing separation between TM- and TE-absorption peaks when increasing the number of cycles from 10 (squares) to 18 (bullets) to 30 (rhombuses). Also, the peak absorption value for the lowest-energy transition is very close for both polarization in the 30-cycles sample. On the other side, the residual polarization-dependence in columnar QDs can be likely linked to a inhomogeneous indium distribution in the QD and to the residual compressive strain which could be re-

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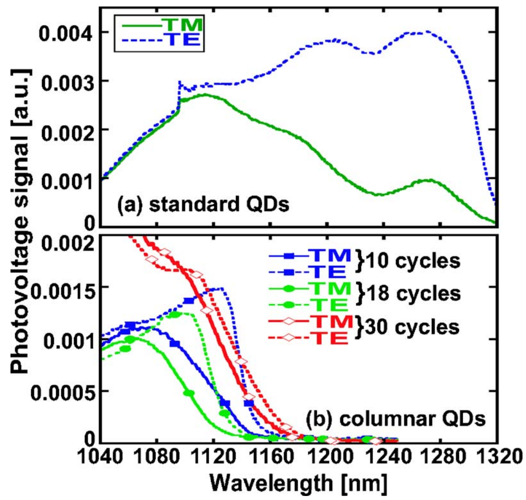

FIG. 4. (Color online) Edge-photovoltage absorption spectra of standard QDs, 10-, 18-, and 30-cycle CQDs.

sponsible that hh- and lh-like states are still energetically separated. In particular, it was already noted[13] that the compressively-strained two-dimensional (2D) quantum well acts from the side to maintain a compressive strain in the CQD, thus pushing the lh-like states deeper in the band. Ideally, a tensile-strained material should be used in the barrier layer of the SL.[13] However, due to the small difference in hh- and lh-like energies in these high-aspect ratio CQDs, we expect that a decreased In content in the 2D layer would be sufficient to achieve gain anisotropy. The In content in the 2D layer can be reduced by using growth conditions which favor In migration toward the CQD.

In summary, we have applied QD shape engineering in order to control the optical polarization anisotropy of QDs. The aspect ratio of columnar QDs is controlled by the number of deposition cycles in the InAs/GaAs superlattice. 30-cycle CQDs present a nanorodlike shape much different from ordinary Stranski-Krastanov QDs. We have fabricated and tested several SOA devices based on CQDs with different number of InAs/GaAs SL cycles. From polarized edge-emitted EL, measuring both integrated intensity and spectra, and photovoltage absorption spectra we observed a very good improvement of TM emission and absorption compared to standard QDs. Although there is still a residual polarization dependence in our columnar QDs, which is related to the nonuniform indium profile, and to anisotropic strain distribution, we expect a promising potential for such kind of QD structures in future SOA devices.

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