Violet-green electrically pumped laser converters with output power over 150 mW

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A violet-green integrated laser converter with a quantum efficiency up to 25.4% and maximum output pulse power of 154 mW at a wavelength of 543 nm has been fabricated on the basis of the II-VI laser heterostructure comprising an active region with five electronically-coupled CdSe/ZnSe quantum dot sheets embedded in a Zn(Mg)SSe/ZnSe superlattice graded-index waveguide. A pulse InGaN/GaN laser diode emitting at 416 nm was used as a pumping source of the laser converter.

Introduction: Compact semiconductor green lasers ($\lambda \sim 530$–550 nm) are strongly demanded for the fabrication of low-cost, high resolution pico-projectors which can be incorporated in smartphones, digital cameras, media players, laptops etc. In spite of significant progress in the development of direct-emitting green InGaN laser diodes (LDs) grown on free-standing GaN substrates ($\lambda = 523$–525 nm, CW operation mode, output power of 38–50 mW, WPE of 2.2–2.3%) [1, 2], alternative ways to obtain semiconductor green lasers are still of great importance because the InGaN LDs demonstrate rather high threshold current density ($J_{th} \sim 9$ kA/cm^2 [2]) steeply increasing with λ.

One of the alternative approaches has been the blue-green laser converter composed of a high-efficiency Cd(Zn)Se/ZnMgSSe laser heterostructure optically pumped by the emission of a blue-violet III-N laser, which was proposed and realised in our early works [3, 4], where the completely optical design was employed. To realise the next generation of converters using blue-violet III-N LDs as pumping sources two essential obstacles should be overcome. First, the threshold power density of II-VI laser heterostructures has to be reduced via structure design and growth optimisation, and, secondly, high-power blue-violet III-N LDs or high-brightness LEDs should appear on the market, which, in turn, is governed by the progress in III-N LD technology.

Recently, utilising II-VI laser heterostructures of conventional design [4], but containing five electronically coupled CdSe/ZnSe quantum dot (QD) planes instead of two, allowed us to achieve the pulse output power in green of 65 mW and the quantum conversion efficiency of 8% for the converter pumped by a commercial blue-violet LD ($\lambda_{exc} = 416$ nm) [5]. The threshold pulse power in that case was 0.65–0.7 W. This Letter reports on the next step in the realisation of high-efficiency violet-to-green electrically pumped laser converters based on the optimised II-VI laser heterostructures with a superlattice (SL) graded-index waveguide (GIW), which demonstrated significantly reduced threshold power density $P_{th} \sim 1.5$ kW/cm^2 [6].

Experiment: The Cd(Zn)Se/ZnMgSSe QD laser heterostructures have been grown by molecular beam epitaxy (MBE) pseudomorphically to a GaAs (001) buffer layer at a substrate temperature $T_s \sim 270°$C, using a two-chamber MBE setup STE3526 (SemiTEq). The elemental Zn, Cd, Mg as well as ZnS compound and Se valve cracking cell (Veeco) were used as MBE sources. The structures consist of bottom and top ZnMgSSe claddings with thicknesses of 1.1–1.4 μm and 20 nm, respectively, a Zn(Mg)SSe/ZnSe short-period SL GIW of a total thickness ~0.3 μm, and an active region comprising multiple electronically-coupled CdSe/ZnSe QD sheets with the nominal CdSe thickness of ~2.8 monolayer, symmetrically or asymmetrically embedded in the SL GIW. The ability of GIW to reduce dramatically the threshold current density in GaAs/AlGaAs QW lasers was demonstrated earlier [7]. The GIW as applied to ZnSe-based laser heterostructures involves a set of $ZnMg_{0.9}S_{0.16}Se$/ZnSe and $ZnS_{0.15}Se$/ZnSe strained short-period (<4 nm) SLs with constant Mg and S compositions and different well-to-barrier thickness ratios and periods to provide the effective energy gap reduction (built-in electric field) to the QD active region. The parameters of the SLs were chosen taking account of complete strain compensation within the waveguide as well as gradual lowering of heavy-hole miniband energy to the active region. The initiation of ZnSe MBE growth on the GaAs buffer was done in a low-temperature (T = 200°C) MEE mode [8] resulting in the extended defect density in the 10^5–10^6 cm^{-2} range.

Transmission electron microscopy cross-section images were obtained using a Philips EM-420 microscope at 100 kV. Photoluminescence (PL) spectra taken from the surface of the structures were excited by a He-Cd laser (~10 mW). The emission of a commercial violet pulse III-N LD ($\lambda = 416$ nm, $\tau_p = 50$ ns, $P_{exc,\ max} = 1.6$ W) was used for the optical pumping of the II-VI laser heterostructures in a transverse geometry. The output surface and edge emission was registered by a CCD camera.

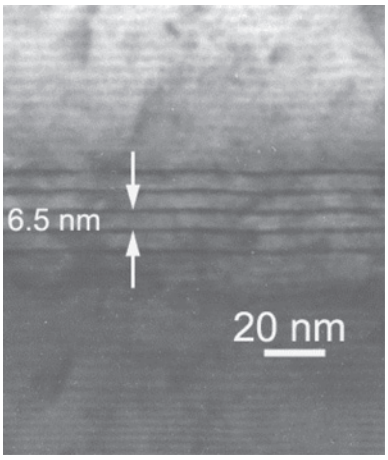

Fig. 1 *Bright field cross-section TEM image of Cd(Zn)Se/ZnMgSSe QD laser heterostructure with GIW waveguide and five QD sheets in active region*

Results and discussion: The II-VI heterostructure design has been optimised using the calculations of optical confinement factors in the plane wave approximation, and the structure with five QD sheets has been chosen as a reasonable compromise between the enhanced optical confinement factor and the ability to avoid the compressive strain relaxation in the multiple CdSe QD sheet structure. A concept of stress compensation applied to the structure design involves 1. growing complex tensile-strained ZnSe-1.5 nm/$ZnS_{0.15}Se_{0.85}$-3.5 nm/ZnSe-1.5 nm barriers between compressively strained QD sheets, which provide efficient tunnelling of non-equilibrium carriers [5], and 2. compensation of the compressive strain induced by the ZnMgSSe/ZnSe GIW SLs by intentionally reducing the average lattice parameter of the central flat-band $ZnS_{0.15}Se_{0.85}$/ZnSe waveguide SL below that of GaAs [6]. The high structural quality of the structure as well as good agreement of intended and as-grown SL period thicknesses are confirmed by the cross-section TEM image shown in Fig. 1.

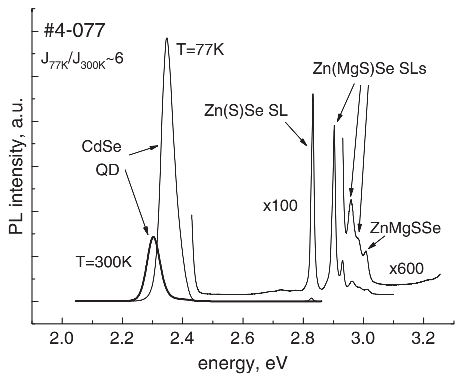

Fig. 2 *Surface PL spectra of Cd(Zn)Se/ZnMgSSe QD GIW laser heterostructure at 77 and 300 K*

The PL spectra from the surface of the GIW laser heterostructure with five QD sheets at 77 and 300K are presented in Fig. 2. The integral PL intensity from QDs at T = 77K is more than two orders of magnitude higher than that from the thickest $ZnS_{0.15}Se_{0.85}$/ZnSe waveguide SL. Moreover, the PL intensities of the well resolved peaks from Zn(Mg)SSe/ZnSe GIW SLs correlate well with the thicknesses of the respective SLs, confirming smooth carrier transport to the active region in assumption of the equal carrier lifetime. The QD peak dominates the PL spectra at room temperature, and the decrease of the integral PL intensity with temperature variation from 300 to 77K is as low as ~6 times.

The above Cd(Zn)Se/Zn(Mg)SSe GIW QD laser heterostructures were used as active elements of the integrated III-N/II-VI LD converter. The laser chips with a short cavity length (~100 μm) were employed to achieve a minimum threshold power value [5]. The maximum room temperature values of the pulse output power of $P_{max} = 154$ mW ($\lambda_{las} = 543$ nm) and quantum conversion efficiency of $\eta = 25.4\%$ have been achieved at the excitation level of $P_{exc} \sim 1.0$ W ($\lambda_{ex} = 416$ nm) for the structure with five QD sheets in the active region placed in the asymmetrical GIW waveguide which provides better overlap of the active region with the fundamental light mode. The threshold excitation power as low as 320 mW (Fig. 3) has been demonstrated, which is about twice less than in [5].

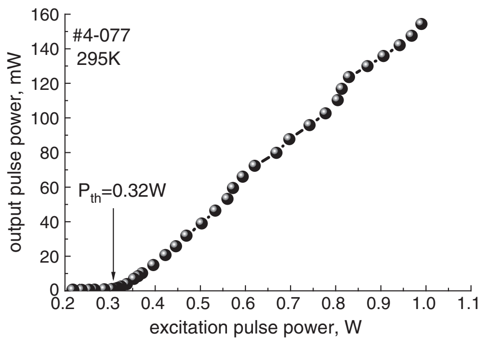

Fig. 3 *Cd(Zn)Se/ZnMgSSe GIW QD laser output against excitation power supplied by blue-violet InGaN/GaN LD ($\lambda_{exc} = 416$ nm, $\tau = 50$ ns, $f = 1$ kHz)*

Laser cavity length 103 μm

Conclusions: Using an asymmetric superlattice-based graded-index waveguide and multiple-sheet CdSe QD active region in the optically-pumped ZnSe-based laser heterostructures has resulted in the decrease of threshold pulse pumping power down to 320 mW and significant improvement of the output parameters of the violet-green III-N/II-VI laser diode converter emitting at ~540 nm.

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