Novel 900 nm diode lasers with epitaxially stacked multiple active regions and tunnel junctions

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A multi-active-region bipolar-cascade edge-emitting laser emitting at nearly 900 nm is presented. The three active regions and two tunnel junctions located in a single waveguide core share the same third-order vertical mode. A slope efficiency of 3.6 W/A was measured with a threshold current density of 230 A/cm². The epitaxial layer stack developed features with very low internal optical losses of 0.7 cm⁻¹. The voltage extrapolated to vanishing current is only 0.3 V larger than 3 times the voltage of 1.4 V originating from the photon energy.

Introduction: Lasers generating short optical pulses with high peak power are key components for LiDAR (Light Detection and Ranging), free-space communication, spectroscopy, metrology, and material processing. In LiDAR systems the distance can be determined by measuring the time of flight of a pulse between the emission by the laser and the detection of its return, after being reflected by an object. Scanning LiDAR systems for autonomous driving require 100 ps – 10 ns long optical pulses with peak powers of more than 100 W. Such pulses can ideally be generated by gain-switched diode lasers where the electrical current injected into the cavity is turned on and off. However, the generation of correspondingly short electrical pulses with high current amplitudes is challenging even with tailored electronic drivers using GaN transistors in the final stage [1]. Such drivers enabled the generation of 4 to 20 ns long pulses with an optical peak power in excess of 600 W at a current of 900 A [2]. In order to avoid these high currents needed to achieve the high peak powers, several laser diodes separated by tunnel junctions can be monolithically stacked in series [3–5]. In the ideal case the slope efficiency of such a nanostack laser scales linearly with the number N of diodes, so that far above threshold there is an N-fold increase of the power at the same injection current. The penalty is an N-fold higher voltage to be applied, for vanishing resistance of the tunnel junction.

Besides the requirements on pulse length and peak power, the emission wavelengths of laser sources to be used for automotive LiDAR systems have to fall into a transparency window of the atmosphere, for example, around 900 or 1500 nm. To reduce the impact of the sunlight shining on the detector, the utilization of narrow-band optical filters is extremely beneficial. This necessitates an emission within a small spectral range, possibly even over a large temperature range, which can be guaranteed by the integration of a Bragg grating into the laser cavity. The cost-effective utilization of a surface grating as demonstrated in ref. [6] is not possible in nanostack lasers because only the laser mode of the uppermost diode would be affected.

Instead of stacking independently working laser diodes, it is also possible to epitaxially stack several active regions alternating with tunnel junctions in a single waveguide core as proposed for automotive LiDAR systems [7]. In order to minimize the impact of the large absorption resulting from the highly doped tunnel junctions and to maximize the modal gain, it is advantageous to utilize a higher-order vertical mode, placing tunnel junctions and active regions into its nodes and antinodes, respectively, in VCSELs [8]. Here the concept is successfully applied to a GaAs-based high-power laser emitting around 900 nm. It is demonstrated that it is possible to achieve very low internal optical losses and a reasonable internal efficiency resulting in a high slope efficiency which scales with the number of active regions (three here) employed.

Device structure and fabrication: The layer stack grown on a GaAs substrate by metalorganic vapour phase epitaxy consists of GaAs buffer, A₀.₅Ga₀.₅As n-cladding, A₀.₅₅Ga₀.₄₅As optical confinement layers around the active regions and tunnel junctions, A₀.₇₅Ga₀.₂₅As p-cladding and GaAs cap. The three 6 nm thick compressively strained InGaAs active quantum wells are sandwiched between tensile-strained GaAsP spacer layers and the two 35 nm thick GaAs tunnel junctions are placed into the antinodes and nodes, respectively, of the third-order mode (Figure 1). The total thickness of the waveguide core including active regions and tunnel junctions is about 5.5 µm. Broad-area lasers were fabricated in a quick process consisting of wet-chemical etching of mesas for lateral optical and electrical confinement, p-metallization (Ti-Pt-Au) on top of the mesas, substrate thinning and n-metallization (Ni-Au-Ge). After processing the wafer is cleaved into bars with lasers having cavity lengths between 600 and 2000 µm which are then characterized unmounted and without facet coating.

Results: Figure 2 shows the power-voltage-current characteristics of 7 as cleaved lasers measured in bar form on a temperature-controlled stage at 20°C under pulsed operation (pulse length 1 µs, repetition frequency 1 kHz). Cavity length and p-contact stripe width are 1000 µm and 100 µm, respectively. The emission wavelength peaks between 895 and 896 nm (compare Figure 3). The measured optical power emitted at one facet was multiplied by a factor of two to get the total power. Below a current of 0.4 A all measured lasers exhibit an excellent uniformity. Above 0.4 A the power-current characteristics of the different lasers deviate slightly from each other. The threshold current determined from the peak value of the second derivative is 0.23 A, resulting in a threshold current density of 230 A/cm². The average slope efficiency obtained from linear fits over the whole current range is as high as 3.6 W/A (1.2 W/A per active region) corresponding to an external differential efficiency of 260% (87% per active region). However, actually the slope efficiency increases from 3.1 W/A slightly above the threshold to 3.9 W/A between 0.8 and 1 A (average value with a variation between 3.83 and 3.95 W/A among the 7 devices). This increase could be caused by an improvement of the carrier injection into the active region at higher bias due to the accompanying change of the profiles of the band edges.

The voltage-current characteristics also show a weak nonlinear behaviour. The series resistance decreases from 1 Ω determined from a linear fit slightly above threshold to 0.7 Ω between 0.8 and 1 A. This could be caused by a non-ohmic behaviour of the tunnel junctions or

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bias, V

Fig 2 Optical total output power (left axis) and applied electrical bias (right axis) versus injection current of 7 lasers measured. Insets: Cavity length L, contact width W, series resistance Rs, bias U₀ extrapolated to zero current, threshold current Iₜh and slope efficiency S

Fig 3 Optical spectra of 7 lasers at injection current of 1 A

Fig 4 Comparison of measured (bullets) and simulated (line) vertical distributions of far-field intensity normalized to the same area

Fig 5 Inverse differential efficiency versus cavity length (bullets). Inset: Internal differential efficiency ηᵢ and internal optical losses αᵢ determined from linear fit (solid line)

a carrier accumulation in the optical confinement layer, increasing its electrical conductivity. The theoretical series resistance obtained from the doping densities and mobilities of the majority carriers in each layer is 0.5 Ω. The deviation between measured and calculated values could indicate that the resistance of the tunnel junctions is still too high. However, one should also keep in mind that the electrical bias was supplied by means of pogo pins having a non-vanishing contact resistance. Parts of the higher series could be also attributed to uncertainties in the doping densities and the theoretical values for the mobilities [9]. The voltage extrapolated to zero current can be written as [10]

\[ U₀ = Nₐ \frac{hc}{\lambda e} + \Delta U \]

where Nₐ, h, c, e, λ, and ΔU are number of active regions, Planck’s constant, speed of light, elementary charge, emission wavelength, and voltage offset. Here the first term amounts to \(3 \times 1.4 \text{ V} = 4.2 \text{ V}\) so that the voltage offset per active region is 0.1 V, a reasonable value.

The optical spectra of the 7 lasers measured (Figure 3) exhibit a single main peak between 895 and 896 nm, indicating that the peak gain wavelengths of all three active regions coincide. Thus the growth of the two tunnel junctions does not result in variations of the compositions and thicknesses between the three InGaAs quantum wells.

The distribution of the far-field intensity measured at 1 A shown in Figure 4 reveals the lasing of the third vertical mode. The agreement with the simulated distribution using a mode solver and Fourier transforming the mode profile taking into account the cosine-squared pre-factor [11] is excellent. Despite the multi-peaked far field, the full angle enclosing 95% of the intensity amounts to only 38° due to the wide waveguide core.

The figures of merits internal optical losses, internal efficiency, modal gain coefficient and transparency current density characterizing the epitaxial layer stack were determined from length-dependent measurements of slope efficiency and threshold current of lasers stemming from different bars with varying cavity lengths. The stripe width is again 100 µm. The slope efficiencies were obtained from a linear fit of the power-current characteristics in a range between 10% and 50% of the maximum power reached. The threshold currents were gained from the peak values of the second derivatives of the power-current characteristics. The extracted inverse differential efficiency versus cavity length and the logarithm of the threshold current density versus inverse cavity length are plotted in Figures 5 and 6, respectively, based on a logarithmic dependence of the modal gain on the current [10]. The low internal losses of 0.7 cm⁻¹ (Figure 4) can be attributed to the low doping (5 × 10¹⁶ cm⁻³) of the confinement layer, resulting in the relatively high electrical series resistance, too. The low losses also reveal that the highly doped tunnel junctions do not contribute to the modal absorption because of their positioning in the nodes of the vertical mode. The internal efficiency of 0.90 per active region (Figure 4) is slightly lower and the transparency
Fig. 6 Natural logarithm of threshold current density divided by \( j_0 = 101 \) A/cm\(^2\) versus inverse cavity length (bullets). Inset: Modal gain coefficient \( G_0 \) and transparency current density \( j_{tr} \) determined from linear fit (line).

current density of 101 A/cm\(^2\) (Figure 5) is slightly higher than those of state-of-the-art single-active-region devices [12]. The modal gain coefficient of 16 cm\(^{-1}\) (Figure 5) is a typical value for high-power lasers.

**Conclusion:** In this Letter, we have presented a novel 900 nm three-active-region edge-emitting laser with an external differential quantum efficiency of 260\% using a single waveguide core. The high efficiency measured at a relatively low current makes us optimistic to achieve a high output power at a very high bias because the layer structure bases on a well-proven design [6]. The fact that all active regions share the same vertical waveguide mode can enable an implementation of a surface Bragg grating for wavelength stabilization, that is, the realization of multi-active-region distributed Bragg reflector or distributed feedback lasers emitting at 905 nm as needed for automotive LiDAR systems.

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