GaAsSb/GaAs quantum dot lasers with strong index-guiding

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***Abstract*—Edge-emitting semiconductor lasers with dense lying GaAsSb quantum dots are improved by strong index-guiding. The differential quantum efficiency is increased up to 77% and the threshold current density decreases to 35%.**

Gain-guiding; index-guiding; semiconductor lasers; quantum dot laser; differential quantum efficiency; threshold current density; characteristic temperature

I. Introduction

Usually gain-guiding is employed in the early stage of semiconductor laser development to get an account of the layer design and epitaxial quality first, before a sophisticated lateral design for index-guiding is added and realized. Especially for quantum dot lasers the way to achieve (lateral) index-guiding is an important issue, since a second epitaxial step (as in the buried heterostructure laser design [1]) for definition of the lateral refractive index profile would be detrimental to the quantum dots due to particle rediffusion. A solution to this problem is strong index-guiding by a deep waveguide rib realized with reactive ion etching. In this contribution experimental results for such laser devices are given – in comparison to the gain-guiding case. The lasers are based on dense lying GaAsSb/GaAs quantum dots (QDs), where results are rarely found in literature so far [2-4].

II. Sample material

A. Sample growth with molecular beam epitaxy

All samples are grown in a *DCA R450* molecular beam epitaxy (MBE) machine. The active region of the lasers consists of layer stacks with GaAsSb quantum dots. With precise control of three growth parameters, i.e. growth temperature, Sb/Ga flux ratio, and nominal coverage, we are able to grow very dense lying optoelectronically active quantum dots up to a density of 9.8×10^{10} cm^{-2} [5,6]. The wavelength can be varied in a wide range from 876 nm up to 1035 nm. For the purpose of this paper, samples are selected, which emit at ≈900 nm wavelength.

B. Sample design and fabrication

Our samples are grown on n-doped (001) GaAs wafers, see Fig. 1. The active region consists of 8 GaAsSb quantum dot layers separated by 50 nm undoped GaAs. The 1500 nm thick $Al_{0.5}Ga_{0.5}As$ claddings are p- or n-doped, respectively.

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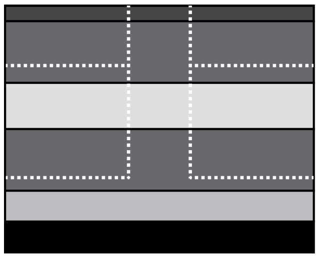

Figure 1. Laser layer design (not to scale). The white dotted lines denote the two etch depths / rib heights

The resonator length of each sample is 1000 µm, the rib width is 100 µm. To compare the laser characteristics gain-guided and index-guided lasers are prepared, the latter with two different etch depths / rib heights. Some of the index-guided samples are etched 1200 nm into the upper cladding, which is 1550 nm thick; the others are etched 3000 nm deep, i.e. through the active region into the lower cladding.

III. Measurements

The output characteristics of all samples at different temperatures are measured under pulsed conditions with a pulse width of 1 µs and 0.1% duty cycle. The differential quantum efficiency and the threshold current density are determined. Furthermore, the characteristic temperatures are extracted from the experimental data.

A. Theoretical expectations

The gain-guided lasers have a lateral effective index step of $\Delta n_{eff} \approx 0$ and should show a higher threshold current density j_{th} and a lower differential quantum efficiency η_d than the index-guided devices acc. to [7]. By increasing Δn_{eff} the threshold current density should rapidly decrease and the differential quantum efficiency should increase. After reaching a maximum in η_d a further increase in Δn_{eff} should lead to a decrease in the differential quantum efficiency and the threshold current density should stay constant [7].

In our case Δn_{eff} is varied by definition of a rib waveguide through a standard dry etching process with different etch depths, i.e. rib heights.

B. Differential quantum efficiency

The laser output characteristics of all samples are measured in a temperature range between -180°C and -30°C, controlled by a thermal resistor heating against LN_2 cooling of the device holder. The differential quantum efficiency η_d is calculated from the slope of the laser characteristics and the emission wavelength of 900 nm [8]. Fig. 2 shows the differential quantum efficiency η_d plotted as a function of sample temperature.

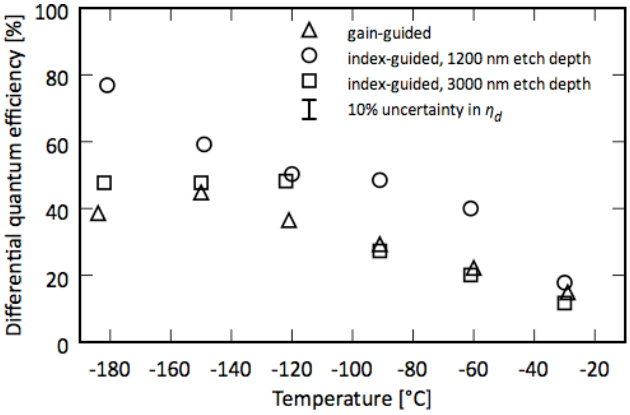

Figure 2. Differential quantum efficiency η_d plotted as a function of sample temperature for lasers with different etch depths, i.e. rib heights

Compared to the gain-guided devices the index-guided ones with 1200 nm etch depth show a higher differential quantum efficiency at all temperatures. It is up to twice as high as in the gain-guided case.

The measured η_d values for the samples etched 3000 nm deep are slightly above the gain-guided ones in the temperature range from -180°C to -120°C. However, above -120°C the differential quantum efficiency is about the same as in the gain-guiding case; obviously etching through the active region into the lower cladding brings no further improvement for η_d as expected acc. to [7] – due to the fact that the lateral mode profile is narrower than the lateral extension of the gain profile in this case.

C. *Threshold current density*

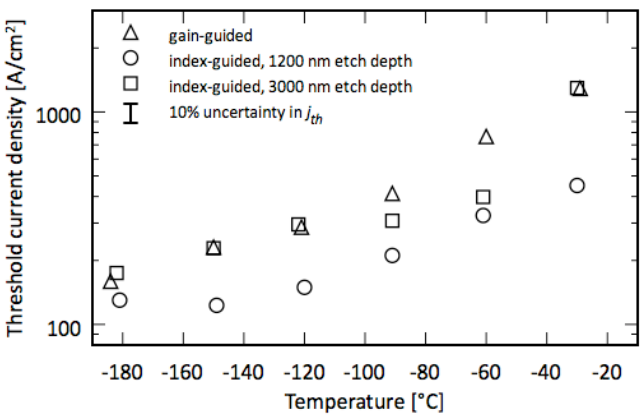

Figure 3. Threshold current density j_{th} plotted as a function of sample temperature for lasers with 1000 µm long and 100 µm wide active regions and different etch depths

The threshold current density j_{th} is determined from the same output characteristics as η_d. Fig. 3 gives the threshold current density j_{th} as a function of sample temperature.

The threshold current densities for the samples etched 3000 nm deep are in the range of those of the gain-guided devices, except for -90°C and -60°C. But very low threshold current densities are achieved for the index-guided devices with 1200 nm etch depth, i.e. only 82% to even only 35% of the value for the gain-guided devices.

D. *Characteristic temperature*

The characteristic temperature T_0 is calculated from the measured data for the temperature ranges -180°C … -120°C and -120°C … -30°C. Table 1 summarizes the results.

TABLE I. CHARACTERISTIC TEMPERATURE T_0

	gain-guided	*index-guided 1200 nm*	*index-guided 3000 nm*
-180°C … -120°C	111 K	415 K	113 K
-120°C … -30°C	56 K	93 K	45 K

Again, the devices with 3000 nm etch depth show no considerable improvement as compared to the gain-guided devices. But the devices with 1200 nm etch depth exhibit considerably higher characteristic temperatures T_0 than the gain-guided devices. Below -120°C it is 3.7-times higher and thus the devices have a much weaker temperature dependence.

IV. DISCUSSION AND CONCLUSIONS

We have reported results on edge-emitting broad area lasers with stacks of GaAsSb quantum dot layers; the dot density is 980 μm^{-2}. We have shown that strong index-guiding due to a deeply dry-etched waveguide rib can improve the output characteristics of the lasers considerably. But further etching down to a level below the active region deteriorates the performance – due to a mismatch of the lateral mode and gain profile widths and possibly due to surface trap states as a result of some rib side wall roughness. Best values achieved for the medium-deep rib and -180°C sample temperature are 77% differential quantum efficiency, 120 A/cm^2 threshold current density, and 415 K characteristic temperature.

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