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# Simulation of threshold operation of GaInNAs diode lasers

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*The advanced three-dimensional fully self-consistent optical-electrical-thermal-gain model of the 1.3-μm (GaIn)(NAs)/GaAs vertical-cavity surface-emitting laser (VCSEL) has been developed to simulate its room-temperature (RT) continuous-wave (CW) performance characteristics and to enable its structure optimisation. The standard GaInNAs VCSEL structure with an intracavity-contacted configuration exhibits very nonuniform current injection into its active region, whereas a uniform current injection is important in long-wavelength VCSELs for low threshold, high-efficiency and stable-mode operation. Therefore we decided to insert an additional tunnel junction within the active-region neighbourhood. The tunnel junction is shown to enhance effectively hole injection via a lateral electron current, with only a modest increase (a small penalty) in voltage drop and series resistance compared to standard devices.*

**Keywords:** GaInNAs laser, GaInNAs VCSEL, simulation of performance characteristics, tunnel junction.

## 1. Introduction

Currently commercially available long-wavelength 1.3-μm diode lasers are based on the (InGa)(AsP)/InP heterostructures. The lasers are usually formed by bonding the above structures to the GaAs/AlAs distributed-Bragg-reflector (DBR) mirrors using the wafer fusion technique. Manufacturing of these lasers, however, requires complicated growth and processing procedures which are probably too expensive for mass-produced commercial devices. Taking additionally into consideration the well established arsenide technology [GaAs/(AlGa)As/AlAs structures with GaAs/AlAs DBRs and oxidised AlAs layers], currently the most promising solution to this problem seem to be to use arsenide structures with such active-gain materials which are lattice matched to GaAs and emit in the 1.3-μm range. Possible candidates are GaAsSb quantum wells, InAs quantum dots (QDs) and the new $Ga_xIn_{1-x}N_yAs_{1-y}$ material, first proposed by Kondow *et al*. [1]. However, GaAsSb diode lasers operate under a very high compressive strain which may be a source of a rapid degradation. QD lasers still exhibit low gain and poor high-temperature characteristics. GaInNAs diode lasers, on the other hand, demonstrate higher possible operating temperatures, higher efficiencies, and higher available output powers than their competitors.

Edge-emitting 1.3-μm (GaIn)(NAs)/GaAs diode lasers have been already reported many times (e.g. Ref. 2). For the optical fibre communication, however, much more suitable are vertical-cavity surface-emitting lasers (VCSELs), mostly because of their higher coupling efficiency and inherently single-longitudinal-mode operation. Because of much more demanding VCSEL technology, first continuous-wave (CW) room-temperature (RT) 1.3-μm GaInNAs VCSELs have just been reported [3].

Technology of the above lasing GaInNAs devices is still very immature. Until now, their development has been strictly based on earlier developments of other VCSELs, whereas physics of (GaIn)(NAs)/GaAs lasers may be somewhat different. Therefore technology centres manufacturing 1.3-μm GaInNAs VCSELs need theoretical support enabling successful designing of these new diode lasers. Hence the main goal of this paper is to develop a comprehensive fully self-consistent optical-electrical-thermal-gain model of an operation of 1.3-μm GaInNAs VCSELs.

## 2. The model

Our three-dimensional (3D) optical-electrical-thermal-gain self-consistent model is composed of four strictly interrelated parts. The optical model is based on the 3D optical effective frequency method and takes into account realistic distributions of both parts (real and imaginary) of a complex index of refraction in all structure layers [4]. The method enables determination of intensity profiles of all radiation modes including their gain and/or loss distributions. Lasing threshold is determined from the condition of a real propagation constant. Current spreading and carrier out-diffusion within the active region are determined solving the Poisson equation and the diffusion equation, respectively. Potential distributions within the n-type and the p-type areas are coupled with each other with the aid of experimental current-voltage characteristics of the p-n junc-

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tion. Using the finite-element approach, current-density and carrier-concentration 3D profiles are determined for the whole device volume. 3D temperature profiles are found solving the thermal conduction equation with a realistic heat-sources distributions including nonradiative recombination, reabsorption of radiation as well as barrier and volume Joule heating. The optical gain spectra are calculated using the classical Fermi golden rule with the Lorentzian broadening mechanism and assuming parabolic bands. All important interactions between individual physical processes are taken into account, including temperature- and composition-dependent thermal conductivities, temperature-, composition- and carrier-concentration-dependent refractive indices, gain and absorption, as well as temperature-, doping- and carrier-concentration-dependent electrical resistivities. The approach is explained in more detail in Ref. 5. The model is intentionally prepared for the PC-class microcomputers to enable its easy application to optimise device structures and to simulate their performance characteristics.

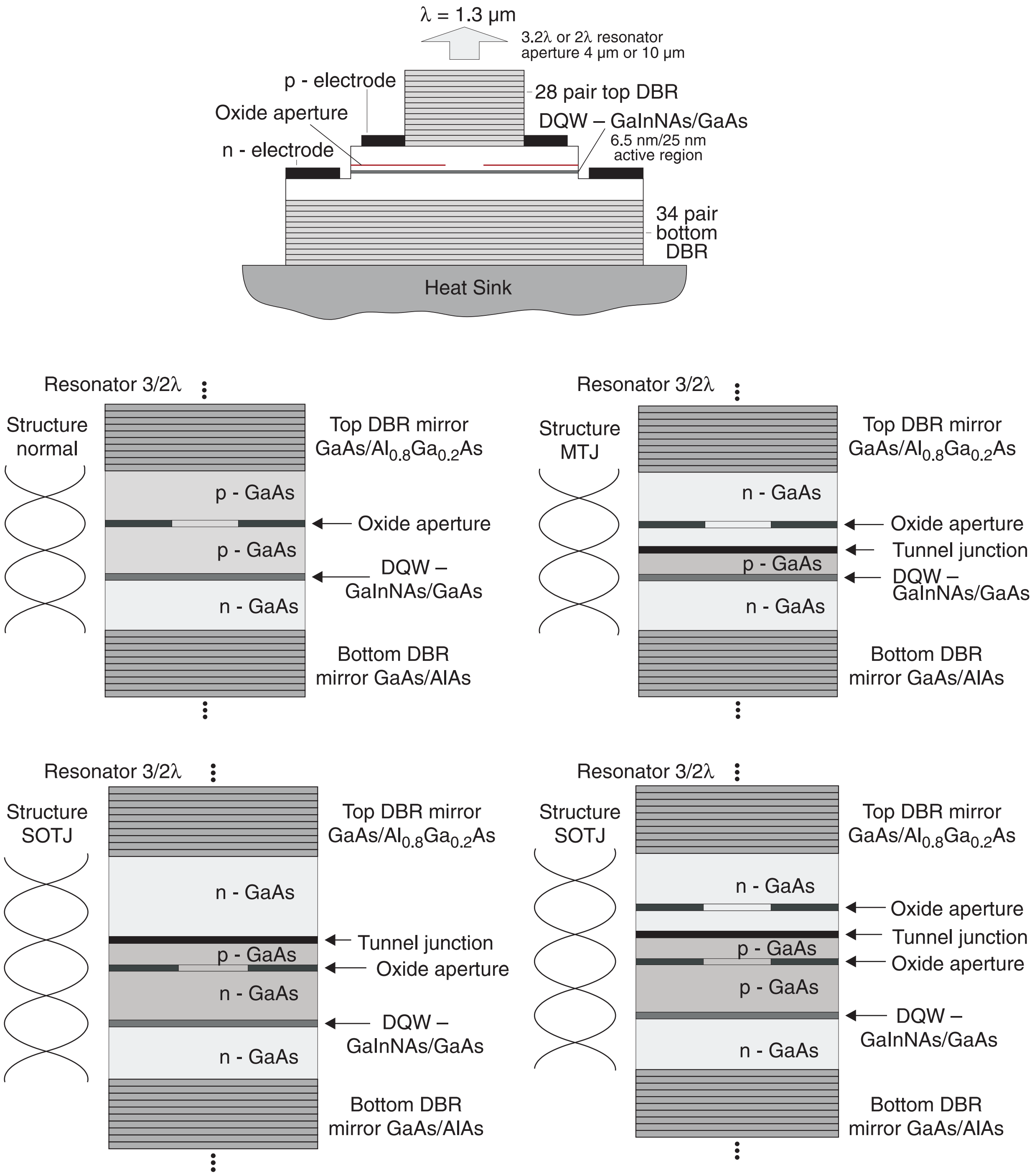


Fig. 1. Schematic cross-section of (GaIn)(Nas)/GaAs VCSEL with various localisations of a tunnel junction.

 

## 3. Results

A standard VCSEL structure of the 1.3-m GaInNAs laser is shown in Fig. 1 [6]. Its active region consists of two 6.5-nm GaInNAs quantum wells (QWs) separated by 25-nm GaAs barrier. Typical upper GaAs/$Al_{0.8}Ga_{0.2}As$ (28 periods) and bottom GaAs/AlAs (34 periods) DBR mirrors are selected. To have the simplest possible DBR design and to avoid the trade-off between electrical problems at heterointerfaces and optical losses due to intervalence-band absorption in p-doped material, we have chosen an intracavity-contacted configuration with both undoped AlGaAs mirrors and a conventional pin doping sequence inside the cavity. This approach is particularly attractive for MBE growth because current is not conducted through the mirrors, hence no grading is required. Despite these efforts, one significant drawback of intracavity contacts is the high lateral series resistance due to the low hole mobility in the p-GaAs layer. Additionally, the standard structure exhibits very nonuniform current injection into its active region. Therefore we decided to insert an additional tunnel junction (TJ). As shown in Fig. 1, its various localizations are possible.

A VCSEL with a tunnel junction for hole injection was proposed and demonstrated in 1984 [7]. The tunnel junction used in our simulation is based on the one reported by Wierer *et al.* [8], so it is composed of 10 nm of $p^+(10^{20}\ cm^{-3})$ GaAs, 10 nm of $n^+(10^{19}\ cm^{-3})$ $In_{0.10}Ga_{0.90}As$, and 10 nm of $n^+(10^{19}\ cm^{-3})$ GaAs. We have assumed that, for this tunnel junction, absorption losses are approximately equal to 1000 $cm^{-1}$ [9] and sheet resistance of $1\times10^{-4}\ \Omega\,cm^2$ [10]. Our numerical modelling shows that an optimised design of the proposed tunnel-junction-connected VCSEL has low sensitivity to the details of the TJ connecting layers because these layers are located at nodes of the laser-mode standing wave.

The standard VCSEL structure (Normal – see Fig. 1) exhibits a very strong current crowding effect near to the active-region edge, whereas nearly insignificant current density is injected into the central part of the active region [Fig. 2(a)]. This causes highly non-uniform carrier concentration distribution: very high close to the active-region perimeter and much lower in the centre. Subsequently, material gain non-uniformity (see Fig. 3) strongly favours unwanted higher-order transverse modes. Besides, for RT CW operation, VCSELs with large-diameter active regions have some thermal problems due to the high threshold current densities [see Fig. 2(b)]. A uniform current injection is important in long-wavelength VCSELs for low threshold, high-efficiency and stable-mode operation. An application of a TJ can solve these problems by employing an n-type highly conductive material for an anode.

Uniformity of current injection is considerably improved in the TJ VCSEL structures (MTJ, SOTJ, DOTJ – see Fig. 2(a). By introducing a tunnel junction in the cavity, one can almost completely replace low electrically conductive p-type GaAs spacer by its n-type counterpart. In this way overall series resistance of the device can be reduced and, more importantly, radial current flow is significantly enhanced. Besides, optical losses due to intervalence-band

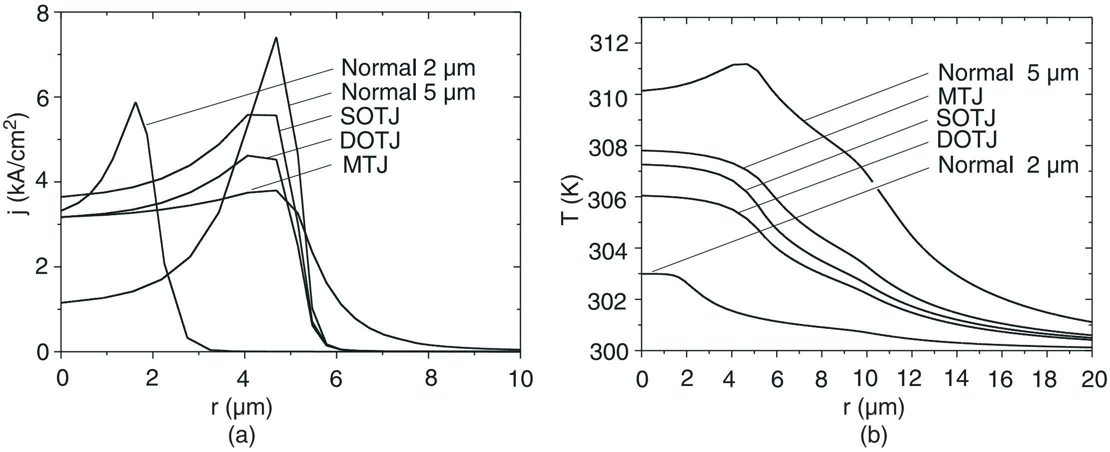


Fig. 2. Radial distribution of the active region current density (a) and radial temperature profile (b) for the modelled GaInNAs VCSELs and their RT CW threshold operation (see Fig. 1 for the notation used).

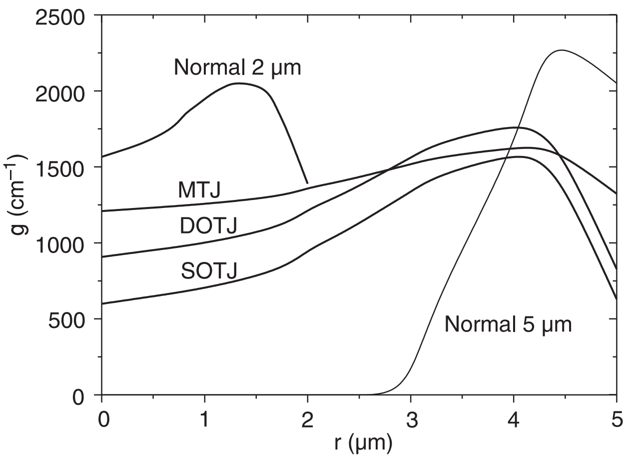


Fig. 3. Radial distribution of optical gain for modelled GaInNAs VCSELs (see Fig. 1 for the notation used).

Table 1. Room –temperature continuous-wave threshold parameters of various designs (see Fig. 1) of GaInNAs VCSELs.

| | $U_{th}$ (V) | $I_{th}$ (mA) | $T_{max}$ (K) | $j_{max}$ (kA/cm$^2$) | Mode | Operation |
|---|---|---|---|---|---|---|
| Normal 2 µm | 2.5 | 0.82 | 303.0 | 5.88 | $LP_{01}$ | single mode |
| Normal 5 µm | 4.5 | 3.88 | 311.3 | 7.42 | $LP_{41}$ | multi mode |
| MTJ | 1.9 | 4.34 | 306.8 | 3.80 | $LP_{11}$ | multi mode |
| SOTJ | 1.9 | 4.28 | 307.3 | 5.58 | $LP_{21}$ | multi mode |
| DOTJ | 1.9 | 3.58 | 306.0 | 4.62 | $LP_{21}$ | multi mode |

absorption in p-doped material (which are much more severe at 1300 nm than at 850 nm [11]) can be avoided. Therefore the dominant excitation of the fundamental $LP_{01}$ mode in the case of RT pulse operation may be expected. For the RT CW operation, however, the dominating mode is $LP_{11}$ or $LP_{21}$, (Table 1).

It has been found in the simulation, that both temperature and gain radial profiles are equally important for transverse mode selection in a GaInNAs VCSEL resonator. When double lateral carrier injection is applied [5], a very non-uniform radial current distribution with high maxima at the edges of the active region is often unavoidable [Fig. 2(a)] in VCSELs with relatively large active regions. This is usually followed by a similarly shaped radial temperature distribution [Fig. 2(b)] enhancing higher-order transverse modes (Table 1). Besides, the mode selectivity becomes very poor which is followed by an unavoidable multi-mode operation. In the case of small devices, however, current density at the structure centre is higher by a factor of three [Fig. 2(a)], which significantly raises a local gain (Fig. 3). Then the fundamental $LP_{01}$ mode becomes distinctly a dominating one (Table 1), which may allow a desirable single mode operation of the device.

## 4. Conclusions

The comprehensive 3D fully self-consistent PC model has been used to simulate a RT CW operation of (GaIn)(NAs)/GaAs VCSELs with $Al_xO_y$ apertures and a tunnel junction. The result for the structure without a tunnel junction shows noticeable nonuniformity. However, all structures with tunnel junctions show almost uniform current injection and lower temperature increases in active layers. Performance characteristics of all these structures are very similar to one another, so selection of the best of them needs additional investigations. The excess absorption loss of the structure with a tunnel junction can be avoided by situating the tunnel junction at the node of the standing wave. So, it is clearly confirmed, that the engineered tunnel junction may improve overall performances of long wavelength GaInNAs VCSELs.

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