

The effects of multiply quantum wells (MQW) on optical and electrical characteristics of AlGaAs lasers with separate confinement heterostructures (SCH).

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Abstract

Optical and electrical characteristics of AlGaAs lasers with separate confinement heterostructures are modeled by using Synopsys's Sentaurus TCAD, and open source software. The results for cases of 2-QW (2 Quantum Wells) and 3-QW structures are compared with these for 1-QW. A significant improvement of useful laser parameters is obtained by increasing the number of Quantum Wells and optimizing the width of waveguides. In particular, the maximum optical efficiency is shown to reach 88 % for a 3-QW structure with optimal width of waveguides. The width of optical intensity profile of MQW lasers increases, leading to lowering maximal light power density passing through laser facets, decreasing the risk of catastrophic damage of mirrors.

1 Introduction

Alferov [1], et al., proposed creating semiconductor-based lasers comprising the use of a geometrically-narrow active recombination region where photon generation occurs, with waveguides around improving the gain to loss ratio (separate confinement

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heterostructures; SCH). That idea dominated largely the field of optoelectronics development in the past years. Due to the relative simplicity and perfection of technology, solid solutions of $Al_xGa_{1-x}As$ are commonly used as wide-gap semiconductors in SCH lasers.

Finding however the best, most efficient structures of SCH lasers is not a task that could be solved easy by experimenting only. Computational modeling is being used recently, as the cost effective approach towards designing new devices as well predicting their characteristics. Moreover, computational modeling offers also new approaches to study physical properties of a device: often, limits of technology do not allow to carry out experiments with accuracy high enough that would allow to verify certain hypothesis.

In our earlier works we first were able to find agreement between our calculations of quantum well energy states and the lasing wavelength observed experimentally [2]. Next [3], several changes in structure and doping of SCH AlGaAs lasers have been shown to considerably improve their electrical and optical parameters. We compared computed properties with these of lasers produced by Polyus research institute in Moscow [4], [5]. In particular, by changing the width of active region (Quantum Well), waveguide width, doping concentration in all laser layers, as well by changing the waveguide profile by introducing a gradual change of Al concentration, and also by introducing variable doping profile of carriers across waveguide, we were able to decrease significantly the lasing threshold current, increase the slope of optical power versus current, and increase optical efficiency up to about 74 % [6]. We have shown [7] that the lasing action may not occur at certain widths or depths of Quantum Well (QW), and the threshold current as a function of these parameters may have discontinuities that occur when the most upper quantum well energy values are very close to either conduction band or valence band energy offsets. These effects are more pronounced at low temperatures, and may be observed also, at certain conditions, in temperature dependence of lasing threshold current as well.

A simple analytical, phenomenological model was shown to describe optical efficiency, $\eta = L/P$ (L is optical power intensity and P is the supplied electrical power), with a high accuracy, by using two parameters only [8].

In Multi-Quantum Well (MQW) structures better characteristics are achievable than in case when one QW is used. Hence, a question is to what an extend yet could we improve properties of laser studied, by using optimized results obtained already and by introducing MQW. The purpose of this work is to compare results for 1, 2, and 3 QW structures and find out optimal widths of waveguides in each case.

One of the fundamental laser characteristics are their threshold current, I_{th} , above which lasing action starts, the slope of optical power versus current, $S = dL/dI$, which is approximately constant for currents just above I_{th} , and lasing offset voltage U_0 . We choose these parameters as characteristics to be compared in modeling.

Table 1: Reference structure of AlGaAs 1-QW SCH laser layers used in computer modeling. d is the width of layers.

No	Layer	Composition	Doping [cm^{-3}]	d [μm]
1	n-substrate	n-GaAs (100)	$2 \cdot 10^{18}$	350
2	n-buffer	n-GaAs	$1 \cdot 10^{18}$	0.4
3	n-emitter	$Al_{0.5}Ga_{0.5}As$	$1 \cdot 10^{18}$	1.6
4	waveguide	$Al_{0.33}Ga_{0.67}As$	$n \approx 10^{15}$	0.2
5	QW	$Al_{0.08}Ga_{0.92}As$	$n \approx 10^{15}$	0.012
6	waveguide	$Al_{0.33}Ga_{0.67}As$	$n \approx 10^{15}$	0.2
7	p-emitter	$Al_{0.5}Ga_{0.5}As$	$1 \cdot 10^{18}$	1.6
8	contact	p-GaAs	$4 \cdot 10^{19}$	0.5

2 Lasers structure and calibration of modeling.

The reference laser we model has a $1000\mu m$ cavity length and $100\mu m$ width, with doping and Al-content as described in Table 1. The Table 2 describes it's experimental parameters. The structure of 2-QW and 3-QW lasers, as shown schematically in Figure 1, is described in Tables 3 and 4, respectively.

Synopsys's Sentaurus TCAD is used for modeling [9]. This is an advanced, flexible commercial computational environment used for modeling a broad range of technological and physical processes in microelectronics world. In case of lasers, some calculations in Sentaurus have purely phenomenological nature. The electrical and optical characteristics depend, primarily, on the following computational parameters that are available for adjusting:

AreaFactor of electrodes, A_e , AreaFactor in Physics section, A_{ph} , electrical contact resistance R_x , and reflection coefficient of laser mirrors, R_l and R_r . There are several parameters for adjustment that are related to microscopic physical properties of materials or structures studied. However, often their values are either unknown exactly or finding them would require quantum-mechanical modeling based on first-principles. This is however not the aim of our work.

In order to find agreement between the calculated results and these observed experimentally we adjust accordingly values of A_e and A_{ph} .

The results for I_{th} and S are all shown normalized by the values for the reference

Table 2: Summary of experimental conditions and laser parameters, for the reference structure described in Table 1.

Temperature [K]	300
Lasing wavelength [nm]	808
Offset voltage U_0 [V]	1.56-1.60
Differential resistance, $r = dU/dI$ [m Ω]	50-80
Threshold current I_{th}^0 [mA]	200-300
Slope of optical power, $S_0 = dL/dI$ [W/A]	1.15-1.25
Left mirror reflection coefficient R_l	0.05
Right mirror reflection coefficient R_r	0.95

laser described in Table 1, I_{th}^0 and S_0 , respectively.

We neglect here the effect of contact resistance, by not including buffer and substrate layers and contacts into calculations (compare with structure described in Table 1). We use instead InnerVoltage parameter available in Sentaurus and treat it as a physical quantity that is related to voltage applied. However, we examined in details results of calculations of optical and electrical characteristics and compared them with these from measurements, finding a reasonably good agreement between them, for lasing offset voltage, threshold current, optical intensity, and differential resistivity [8].

3 Threshold current and dL/dI for 2-QW and 3-QW structures.

We choose to use threshold current I_{th} and the slope of optical intensity versus current, $S = dL/dI$ as the most important technologically laser parameters, when comparing lasers with various structures. The advantage of using them is also in that that these could be easy extracted semi-automatically from a large collection of data sets. Details of data analysis are described better in [8] and also on our laboratory web site¹.

Computation was performed as a function of the width d_{w1} , for a certain set of

¹Web: www.ostu.ru/units/ltd/zbigniew/synopsys.php

Table 3: Two Quantum Wells: Structure of AlGaAs SCH laser layers. d is the width of layers.

No	Layer	Composition	Doping [cm^{-3}]	d [μm]
1	n-emitter	$Al_{0.5}Ga_{0.5}As$	N $1 \cdot 10^{18}$	1.6
2	waveguide	$Al_{0.33}Ga_{0.67}As$	N $1 \cdot 10^{15}$	d_{w0}
3	QW	$Al_{0.08}Ga_{0.92}As$	N $1 \cdot 10^{15}$	0.012
4	waveguide	$Al_{0.33}Ga_{0.67}As$	N $5 \cdot 10^{14}$	d_{w1}
5	QW	$Al_{0.08}Ga_{0.92}As$	P $1 \cdot 10^{15}$	0.012
6	waveguide	$Al_{0.33}Ga_{0.67}As$	P $1 \cdot 10^{15}$	d_{w0}
7	p-emitter	$Al_{0.5}Ga_{0.5}As$	P $1 \cdot 10^{18}$	1.6

constant values of d_{w0} (see Fig. 1).

Figures 2 and 3 show results for I_{th}/I_{th}^0 and S/S_0 , respectively, for the case of 2-QW structures, while Figures 4 and 5 show similar results for 3-QW structures. In these Figures, where no data points are present for certain values of d_{w1} - there is no lasing action observed there. The meaning of lines in Figures 2-4 is to guide the eyes only. They are drawn however by using least-squares fitting of the data points to simple power-law functions.

As we see, a significant reduction of threshold current is observed for both, 2-QW and 3-QW structures, if compared with the value for the reference laser with 1-QW. Also, a large increase of dL/dI is found, more significant in case of 3-QW structure.

4 Optical efficiency.

Figures 6 and 7 illustrate how optical efficiency as a function of voltage applied depends on geometry of lasers, for several cases of waveguide parameters d_{w0} and d_{w1} that correspond, approximately, to the maximum values of optical efficiency. The largest optical efficiency achieved, of about 88%, is for 3-QW structure when d_{w0} is about 100 nm, and d_{w1} of about 29 nm.

We proposed [8] that a modified exponential dependence describes very well current-voltage characteristics just above the lasing offset $U > U_0$:

$$I(U) = I_{th} \cdot \exp(C \cdot (U - U_0) + D \cdot (U - U_0)^2), \quad (1)$$

Table 4: Three Quantum Wells: Structure of AlGaAs SCH laser layers. d is the width of layers.

No	Layer	Composition	Doping [cm^{-3}]	d [μm]
1	n-emitter	$Al_{0.5}Ga_{0.5}As$	N $1 \cdot 10^{18}$	1.6
2	waveguide	$Al_{0.33}Ga_{0.67}As$	N $1 \cdot 10^{15}$	d_{w0}
3	QW	$Al_{0.08}Ga_{0.92}As$	N $1 \cdot 10^{15}$	0.012
4	waveguide	$Al_{0.33}Ga_{0.67}As$	N $5 \cdot 10^{14}$	d_{w1}
5	QW	$Al_{0.08}Ga_{0.92}As$	N $5 \cdot 10^{14}$	0.012
6	waveguide	$Al_{0.33}Ga_{0.67}As$	P $5 \cdot 10^{14}$	d_{w1}
7	QW	$Al_{0.08}Ga_{0.92}As$	P $5 \cdot 10^{14}$	0.012
8	waveguide	$Al_{0.33}Ga_{0.67}As$	P $1 \cdot 10^{15}$	d_{w0}
9	p-emitter	$Al_{0.5}Ga_{0.5}As$	P $1 \cdot 10^{18}$	1.6

where C and D are certain fitting parameters. It is convenient to rewrite 1 in dimensionless variables:

$$i(u) = \exp\left(\frac{1}{\alpha} \cdot (u - 1) \cdot [1 + \beta \cdot U_0^2 \cdot (u - 1)]\right), \quad (2)$$

where we defined: $i(u) = I(U)/I_{th}$ and $u = U/U_0$, $\alpha = r \cdot I_{th}/U_0$, $\beta = U_0 \cdot D/C$, and we defined also $r = dU/dI = \frac{1}{I_{th} \cdot C}$, which is differential resistivity just above U_0 .

Hence, the optical efficiency, $\eta = L/(U \cdot I)$, is given by:

$$\eta(u) = \frac{S}{U_0} \cdot \frac{i(u)-1}{u \cdot i(u)}, \quad (3)$$

where $i(u)$ is given by Eq. 2.

Like in case of 1-QW structure ([8]), the data shown in Figures 6 and 7 are described by 3 with a high accuracy, by using two fitting parameters only, α and β (except of I_{th} and U_0 that may be found in a straightforward way).

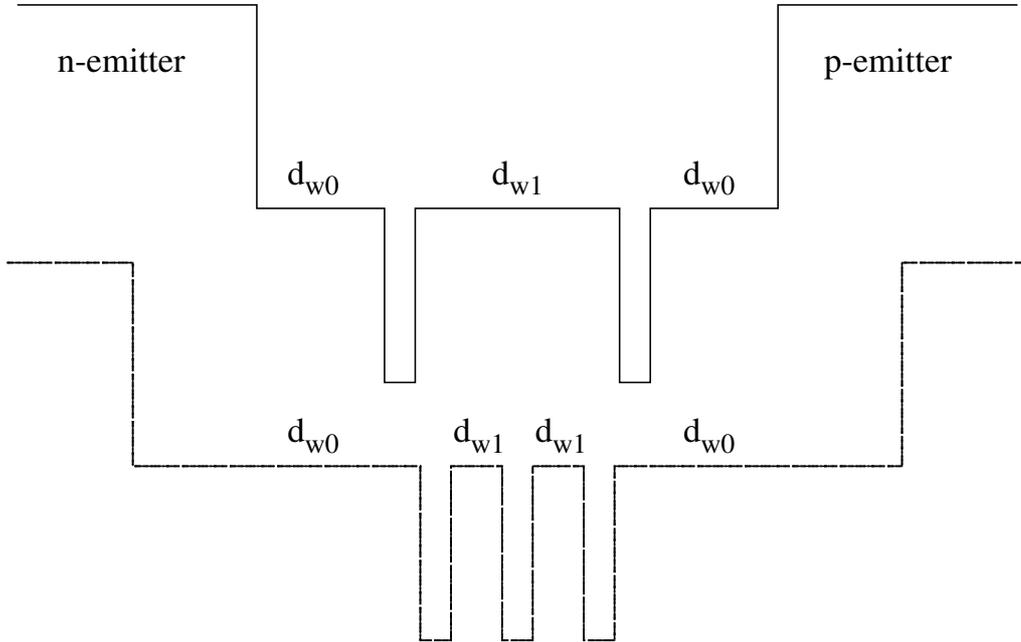


Figure 1: Schematic structure of energy gap for MQW lasers modeled, with 2- and 3-quantum wells (the upper and lower diagrams, respectively). d_{w0} and d_{w1} are widths of waveguide regions. Active regions remain the same and their width is $12nm$. Doping types and concentrations are shown in Tables 3 and 4.

5 Lasing offset voltage U_0 .

As shown by Eq. 3, optical efficiency depends on lasing offset voltage and it is desirable to have it's value as low as possible. In literature, there is no a simple formula that would describe variations of U_0 with physical material parameters and geometrical structure of a laser. One of reasons for that is that the $I - V$ characteristics depend strongly in a too complex way on density of states and number of captured carriers in QW. The number of QW levels and their separation, as well their energy distance from conduction band or valance band offsets are a function of QW geometry as well [7]. Therefore, it is useful to have an insight into what kind of dependencies might be obtained as a function of waveguide width. Performing real experiments of that kind is unrealistic: there is no way to control laser geometrical dimensions during technological process with sufficient, required accuracy. Instead,

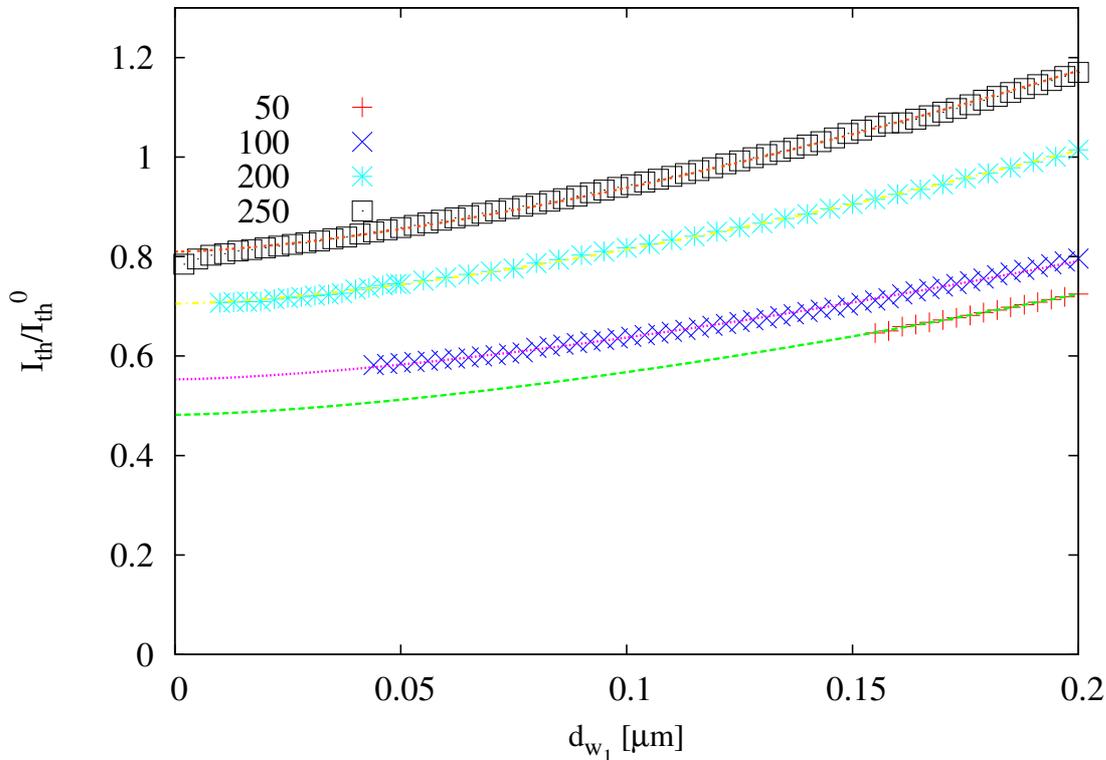


Figure 2: Two Quantum Wells: threshold current, I_{th} , normalized by I_{th}^0 , as a function of the width of waveguide in the center, for a few width values of other two waveguides (in nm), as indicated in the Figure.

a large spread of the data points would be obtained and no conclusions could be drawn².

We find in our modeling that a good accuracy of determining U_0 is gain versus voltage curve in a near range of voltage values below U_0 . We use a linear extrapolation of the data towards the maximum value, which is constant above U_0 in Sentaurus. The results presented in Fig. 8 were obtained that way. This method is the most accurate in our case and allows for easy, semi-automatic analysis of large collections of data sets.

As a result of a complex interplay between density of states in quantum wells when waveguide width d_{w1} changes, clear discontinuities are observed in $U_0(d_{w1})$, as shown on Fig. 8.

²In [7], we point out however that there are hypothetically ways that could bypass these experimental problems.

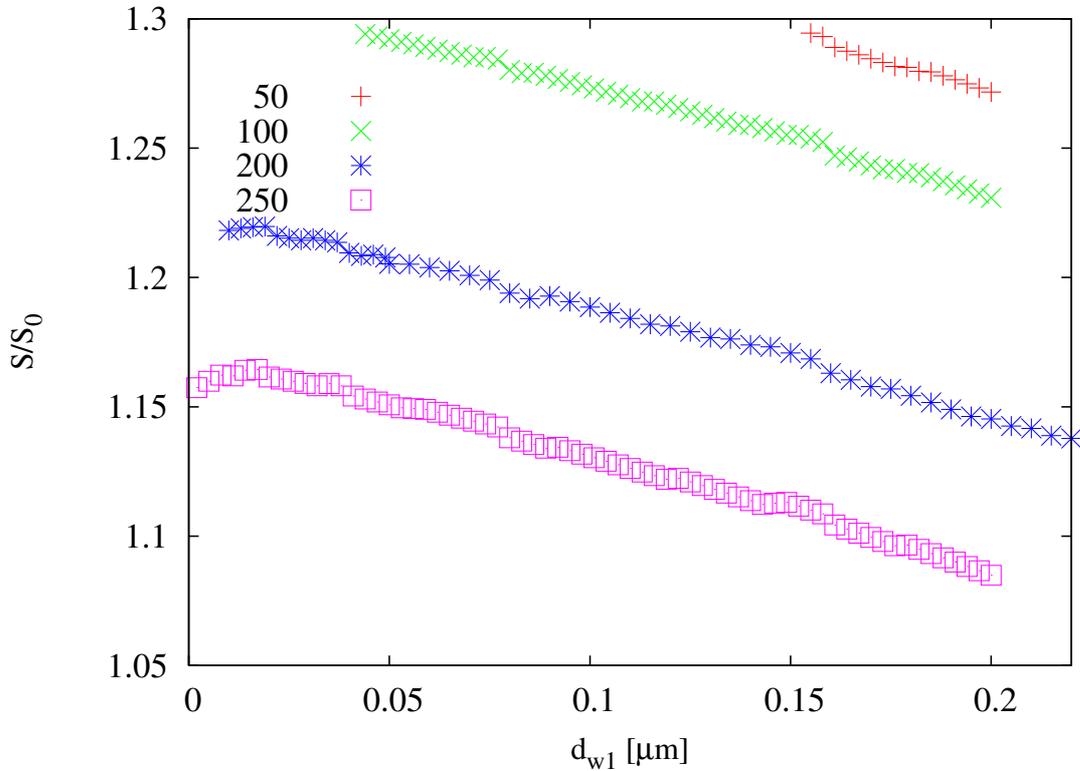


Figure 3: Two Quantum Wells: Slope of optical power, $S = dL/dI$, normalized by S_0 , corresponding to the data in Figure 2.

One should however be cautioned here. Somewhat similar effects might be an undesired, artificial artifact of improperly conducting the modeling calculations: results depend for instance on how the mesh changes when geometrical parameters of modeled structure change. In our case, we kept the number of mesh points constant, independent of geometrical sizes of laser layers.

6 Optical intensity profiles for 3-QW structure.

When changing the structure and width of waveguides we gain some control over the power distribution over the laser facets. That way we may possibly decrease the effects that limit the maximal output power, that are caused by thermal damage to mirrors.

One of the simplest ways to characterize optical intensity profiles is to use their half-width, i.e. the distance from the laser center where optical intensity decreases

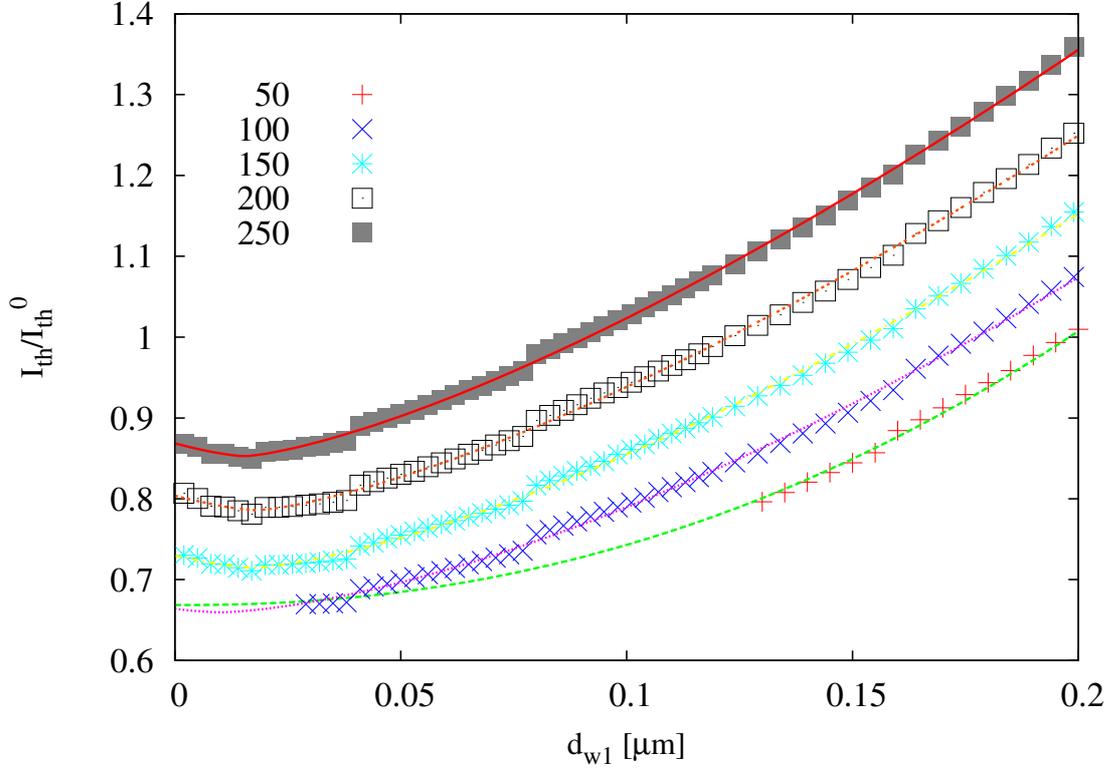


Figure 4: Three Quantum Wells: threshold current, I_{th} , normalized by I_{th}^0 , as a function of the width of two waveguides in the center, for a few values of other two waveguides width (in nm), as indicated in the Figure.

to half of its maximal value, Δw .

The half-width in Figure 9, is given by linear dependence on w_0 : $\Delta w = 0.409 \cdot w_0 + 0.161$ (when $w_1 = 0.130 \mu m$).

When similar analysis is done for the case of w_1 width of $0.029 \mu m$, we obtain the following expression for the half-width of optical profile intensity: $\Delta w = 0.394 \cdot w_0 + 0.111$.

For the case of w_1 width of $0.219 \mu m$, we obtain the following expression: $\Delta w = 0.444 \cdot w_0 + 0.2034$.

By additional analysis, we find that the following general relation describes well the dependence of the half-width of optical intensity profile on w_0 and w_1 :

$$\Delta w = (0.392 + 1.069 \cdot w_1^2) \cdot w_0 + 0.487 \cdot w_1 + 0.097 \quad (4)$$

where all quantities are in μm .

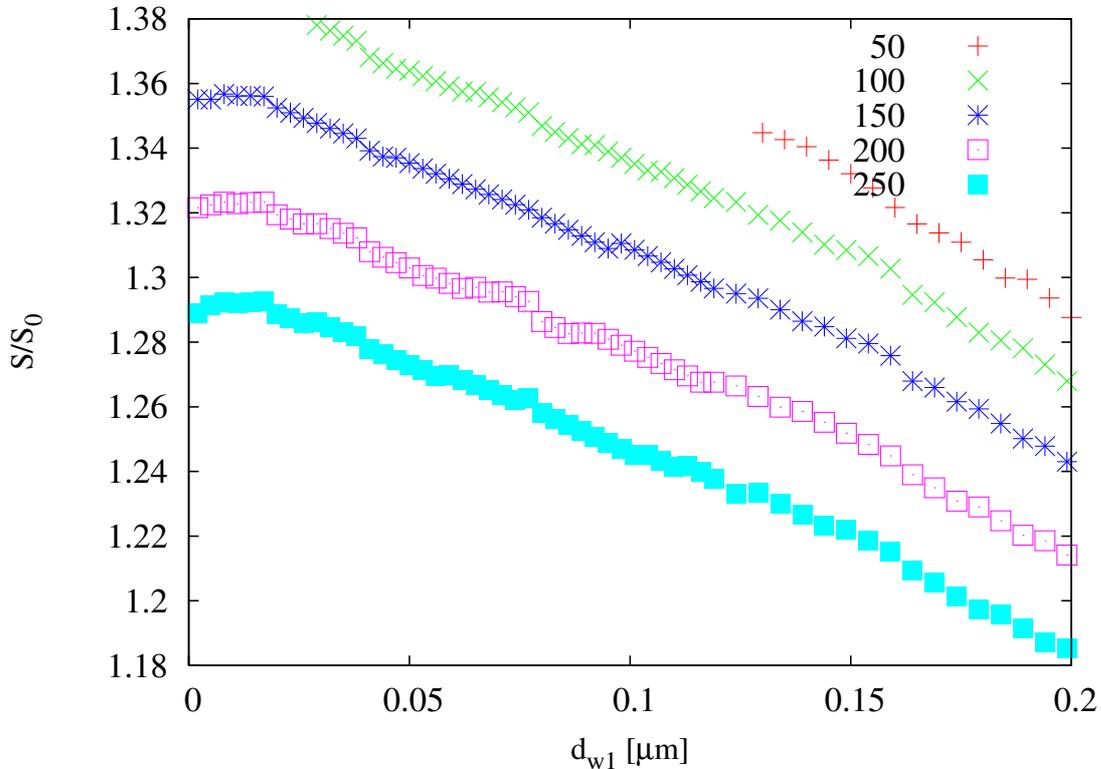


Figure 5: Three Quantum Wells: Slope of optical power, $S = dL/dI$, normalized by S_0 , corresponding to the data in Figure 4.

7 Summary and Conclusions.

By using Synopsys's Sentaurus TCAD, and open source software we performed computer modeling of optical and electrical characteristics of AlGaAs lasers with separate confinement heterostructures, when 2 and 3 quantum wells are present. We compared results with these for 1-QW laser calibrated to reproduce characteristics of lasers produced at Polyus research institute in Moscow ([4] and [5]).

It was shown that a significant improvement of laser parameters is obtained in case of MQW lasers, when the width of waveguides is optimized.

The maximum optical efficiency achieved reaches 88 % for a 3-QW structure.

The width of optical intensity profile of MQW lasers increases, leading to lowering maximal light power density passing through laser facets, decreasing the risk of catastrophic damage of mirrors.

It has been shown, by examining lasing offset voltage, that laser characteristic parameters are expected to be discontinuous functions of waveguide's width.

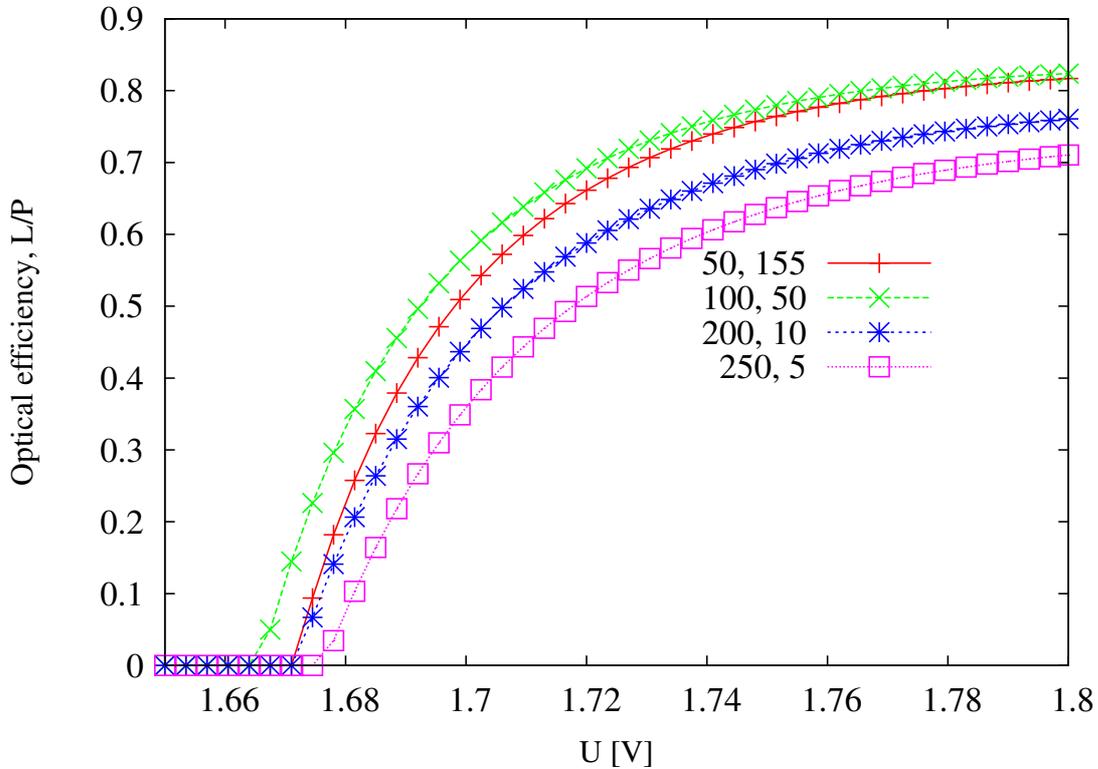


Figure 6: Two Quantum Wells: Optical efficiency as a function of voltage applied for several combination of waveguides widths, as shown in the Figure: the first number is the width d_{w0} , the second one is d_{w1} (in nm).

We did not study possible more complex structures. In particular, as modeling results show in case of 1-QW ([3] and [6]), introducing gradual doping profiles in waveguides, and also gradual changes to Al concentrations there may lead to significant improvement of laser parameters. Also, the assumed here width of quantum wells, is close only to the optimal one.

Moreover, it is tempting to create structures with variable width of active regions (but the same lasing frequency). These would have, for instance, different characteristics as a function of temperature.

8 Acknowledgement

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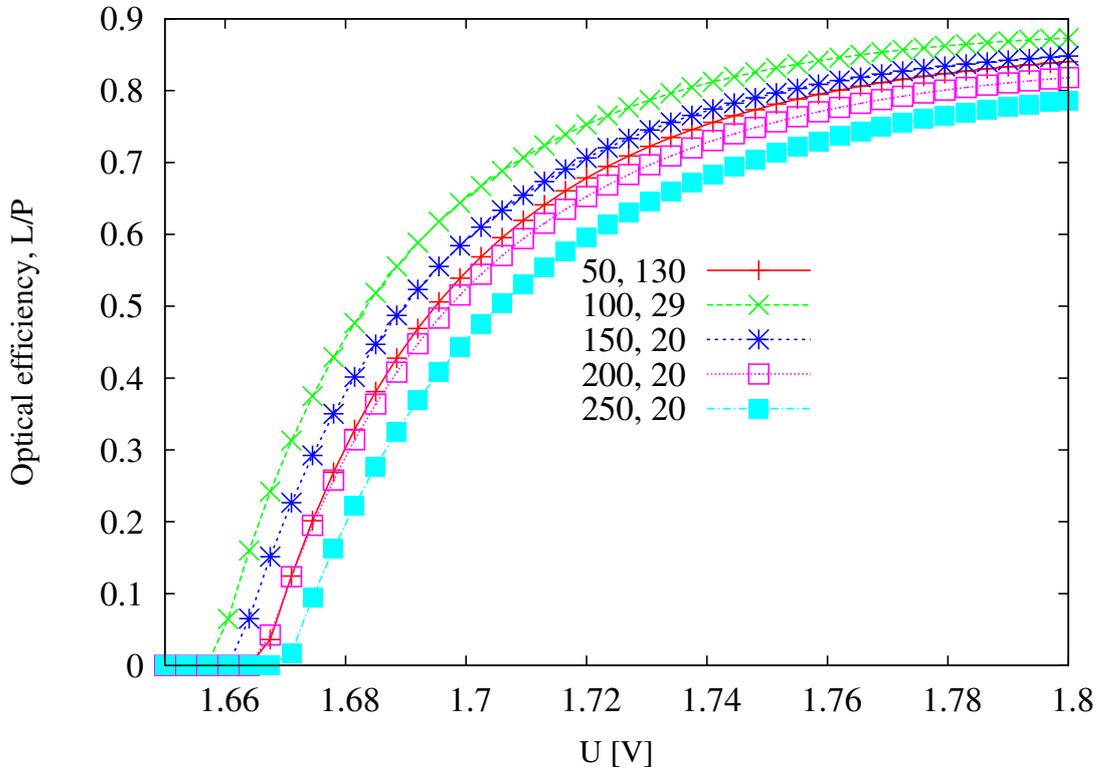


Figure 7: Three Quantum Wells: Optical efficiency as a function of voltage applied for several combination of waveguides widths, as shown in the Figure: the first number is the width d_{w0} , the second one is d_{w1} (in nm).

indebted for valuable comments and discussions to A. A. Marmalyuk of Research Institute "Polyus" in Moscow.

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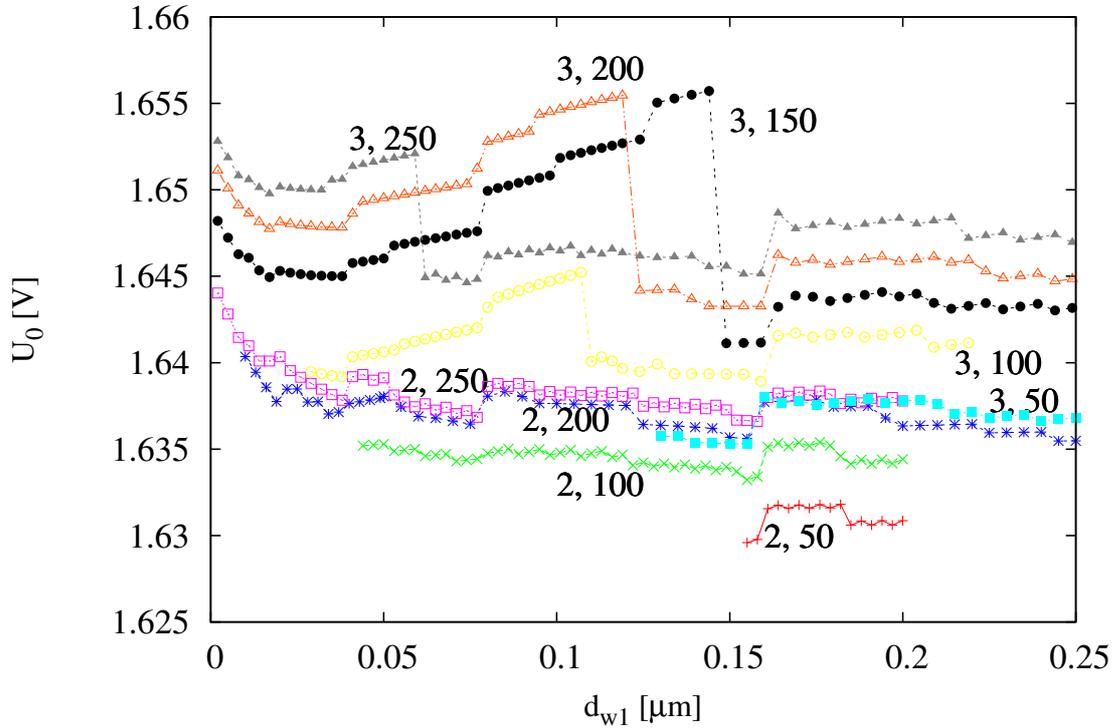


Figure 8: Two and three Quantum Wells: lasing offset voltage U_0 as a function of waveguide width d_{w1} . The first number in labels denotes 2- or 3-QW structure, the second one the width d_{w0} in nm .

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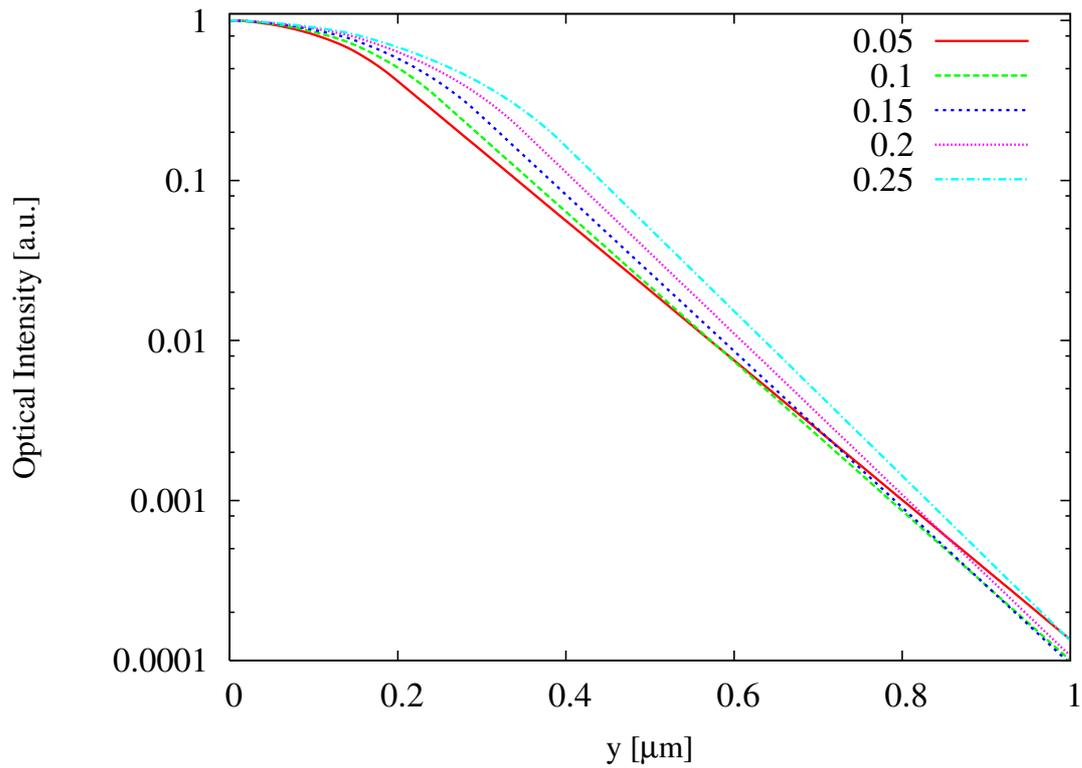


Figure 9: Three Quantum Wells: Optical power intensity as a function of distance from the laser center, y . Calculations were done for the width $d_{w1} = 0.130\mu m$, and several values of d_{w0} (in nm), as shown in the Figure. All curves are normalized to value of 1 at maxima.