Development of a semiconductor optical gate heterostructure design with a bulk active region for laser intensity modulators operating in the 1520−1650 nm spectral range

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Within the framework of one-dimensional numerical simulation, the regions of optimal design parameter values were determined for a heterostructure with a bulk active region based on an InGaAs ternary solid solution and a modulator chip used as a semiconductor optical gate. A multi-parameter search was performed for acceptable sets of parameters (modulator length, active element width, optical confinement factor in the active region, and its thickness) at which the optical gate chip can provide the required values of extinction ratio and small-signal gain. It was found that the extinction ratio and small-signal gain values increase significantly with an increase in the optical confinement factor in the active region; however, the optimal set of parameters should be identified by conducting a global search. It is shown that increasing the optical confinement factor in the active region up to 12% ensures the required optical gate characteristics at short modulator lengths (1200 μm) and an active region thickness of 80 nm.

Keywords: semiconductor optical gate, small-signal gain, extinction ratio, numerical simulation, InGaAs bulk active region.

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1. Introduction

Laser radiation intensity modulators based on semiconductor heterostructures providing for the ability to both modulate the intensity of the optical signal and amplify it are in demand for the wide spectrum of practical applications, which is related to their compact size, high efficiency, and the ability of integration. For example, in the wavelength division multiplexing systems, the solution is in demand to the problem of adding new optical channels to the common flow and extracting the signals from the flow [1,2], which may be solved using arrays of optical gates, providing for high extinction ratio of the modulator (integral characteristic of extinction ratio, defined as the ratio of the optical power at the outlet in the open state to the power in the closed state) for a wide range of wavelengths, for example, 1520−1650 nm. Other important applications are rangefinders and lidar systems for autonomous vehicles. Use of such modulators makes it possible to implement the heterodyne principle of detection at the expense of using a spectrally stabilized source of laser radiation with a narrow generation line [3]. You can separately identify the systems of information transmission in a free space, which require modulators with high extinction ratio between the on and off states to improve the signal–noise ratio [4]. Recently the area is developing actively, which is related to the design of optical logical circuits, including those built on active components, for example, an optical amplifier-modulator of laser radiation, at the expense of implementation of the ability of fast switching between the two states with high extinction ratio [5].

Besides, in such applications it is important to provide both for the maintenance of polarization and to make the system polarization-insensitive [6]. One of the approaches solving the problem of polarization insensitivity is the use of a heterostructure with a bulk active region [7]. If quantitative characteristics are mentioned, the desired values of the ratios of dynamic amplitude extinction between the on and off states (for the generation of the optical pulse) must exceed 40 dB, and the small-signal gain must be ≥ 5 dB. In this case the problem becomes relevant to find the optimal heterostructure design, providing for the optimal operating characteristics: maximum gain, maximum extinction ratio, low operating current of modulator pumping. The search for the optimal characteristics of the structure and the chip of the modulator is feasible within numerical modeling [8].

In this paper the optimal characteristics were sought for the semiconductor optical modulator with the heterostructure on the basis of the bulk active region InGaAs using a numerical model, including the system of three stationary equations along light propagation in the modulator [9]: equation for concentration of the charge carriers and two equations for concentration of photons that propagate towards each other.

2. Model description

The model of the semiconductor optical modulator is described in paper [9] and includes a system of three stationary equations:

$$\frac{dn}{dt} = 0 = \frac{I}{qV} - (An + R_{\text{sp}} + Cn^3) - \frac{R_{\text{st}}}{1 + \varepsilon S_\Sigma},$$

$$\frac{dS_+}{dz} = \left(\frac{\Gamma g}{1 + \varepsilon S_\Sigma} - \alpha_1\right) S_+ + \frac{1}{2v_g}\Gamma\beta_{\text{sp}} r_{\text{sp}},$$

$$-\frac{dS_-}{dz} = \left(\frac{\Gamma g}{1 + \varepsilon S_\Sigma} - \alpha_1\right) S_- + \frac{1}{2v_g}\Gamma\beta_{\text{sp}} r_{\text{sp}}$$

with boundary conditions:

$$S_+(0) = S_0 + R_1 S_-(0),$$

$$S_-(L) = R_2 S_+(L),$$

where n — concentration of charge carriers, S_+ — concentration of photons, propagating to the right from the mirror with reflectivity R_1 and coordinate $z = 0$ to the mirror with the reflection ratio R_2 and coordinate $z = L$, S_- — concentration of photons, propagating to the left from the mirror with the reflectivity R_2 and coordinate $z = L$ to the mirror with the reflection ratio R_1 and coordinate $z = 0$, S_0 — the source of concentration of photons arriving to the modulator (coordinate of the source $z = 0$), defined via the level of inlet optical power, S_Σ — total concentration of photons $(S_+ + S_-)$, I — current flowing through the modulator, q — elementary charge, L — modulator length, w — width of the active element, d — thickness of the active element, thickness of the bulk active region, V — volume of the active region, equal to the product of three parameters: length of the modulator L, width of the active element w, total thickness of the active element d, n_{gr} — group refraction index in the modulator waveguide, v_{gr} — group speed, ε — gain compression factor, Γ — optical confinement factor in the active region, α_i — internal optical losses, A — Shockley–Read–Hall nonradiative recombination coefficient, B — radiative recombination coefficient, C — nonradiative Auger recombination coefficient. The spontaneous recombination rate R_{sp} was determined through the product of the radiative recombination coefficient B and the squared concentration of charge carriers, and the stimulated recombination rate R_{st} — through the product of the group speed v_{gr} and material gain g and the total concentration of photons S_Σ. Within the considered model the internal optical losses are accepted as $\alpha_i = 4\,\text{cm}^{-1}$, reflection ratios R_1 and R_2 — 0 and 0.001 accordingly. It is assumed that the gate operates at the fixed wavelength, therefore the spectral unevenness of gain, which could manifest itself at the inlet broadband signal, is not taken into account in the model.

Material gain g is determined from the three-parameter gain model [10]:

$$g(n) = g_0 \cdot \log\big((n + N_s)/(N_{\text{tr}} + N_s)\big),$$

where N_{tr} is transparency carrier density, $N_{\text{tr}} = 1.1 \cdot 10^{18}\,\text{cm}^{-3}$ for the bulk active region [10], g_0 is material gain in the case when the concentration of charge carriers n is equal to the concentration of transparency N_{tr}, $g_0 = 3000\,\text{cm}^{-1}$ [10], N_s is the parameter for the case, when the concentration of the charge carriers n is equal to zero, providing for the equality of absorption gain due to band-to-band transitions, $N_s = 5 \cdot 10^{18}\,\text{cm}^{-3}$ [10].

3. Findings and discussion

The described model is used to conduct multiparametric calculations of the extinction ratio (ER) as the ratio of outlet optical powers with the change of the pumping current from the specified level (in this paper 250 mA) to 0 mA, which corresponds to the transition from the open to the closed state at the fixed value of the power of the inlet signal of 1 mW. Small-signal gain ($Gain$) was defined at the specified level of pumping current (in this paper 250 mA) at inlet power of 0.001 mW from the comparison of the optical power at the outlet to the power at the inlet to the modulator.

Search for the acceptable set of parameters (modulator length L, active element width w, active region thickness d, optical confinement factor in the active region (Γ-factor)), which characterize the design of the optical gate chip, was carried out for the condition when the extinction ratio ER would turn out to be at least 40 dB (10 000 times), and small-signal gain $Gain$ would exceed 5 dB. For this purpose the multiparametric calculations ER and small-signal gain $Gain$ were conducted for the following permissible ranges of parameter change: length of the modulator L in the range from 500 to 3000 μm, width of the active element w in the range from 1.5 to 8 μm, thickness of the active region d in the range from 20 to 80 nm and optical confinement factor in the active region (Γ-factor) in the range from 5 to 15%. The ranges of parameters are selected on the basis of technological assumptions as permissible in the practical implementation of the developed structures of heterostructures and chips. The specific results are shown in Figures 1–6.

Let us consider the specific charts of the extinction ratio (ER) and small-signal gain ($Gain$) values. Figure 1 and 2 show the dependences of the extinction ratio (Figure 1) and small-signal gain (Figure 2) on the length of the modulator and thickness of the active region at the fixed values of the optical confinement factor in the active region and the width of the active element: Γ-factor = 5%, $w = 5\,\mu$m.

On the chart ER (Figure 1) you can see that ER decreases with the increase of d at the fixed L, and the longer is the modulator, the higher is the speed of the decrease ER with the increase of d. Dramatic growth of the extinction ratio

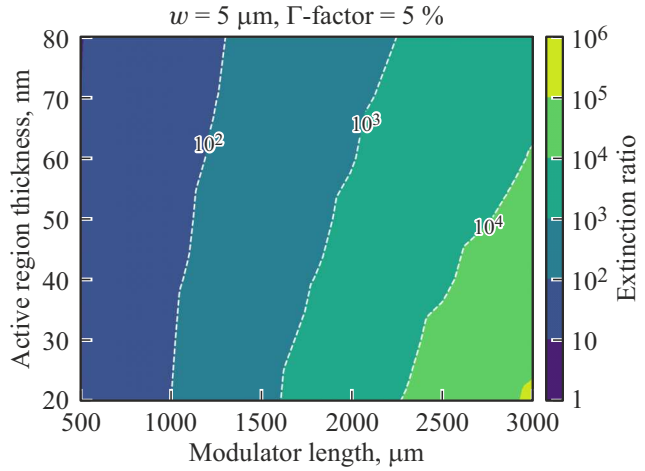


Figure 1. Extinction ratio depending on parameters d and L at $w = 5\,\mu$m, $\Gamma = 5\,\%$.

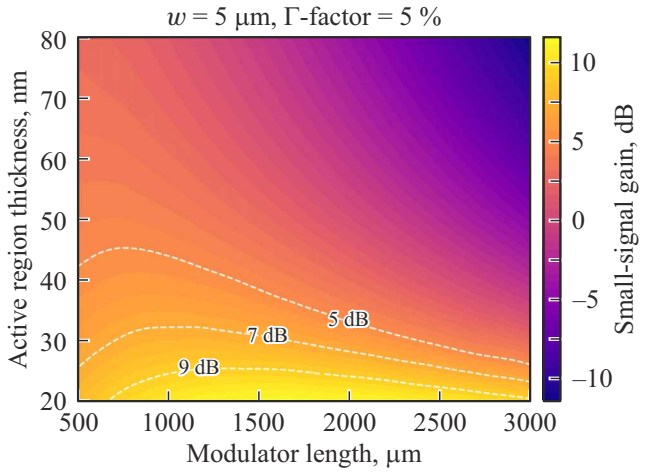


Figure 2. Small-signal gain depending on parameters d and L at $w = 5\,\mu$m, $\Gamma = 5\,\%$.

ER with the increase of the modulator length is related to the fact that the longer chip in the off state ($I = 0$) absorbs light more strongly, and in the on state ($I = 250$ mA) it provides for higher gain. On the chart of Figure 2 you can see that $Gain$ decreases with the increase of d at the fixed L, and the longer is the modulator, the higher is the speed of decrease $Gain$ with the increase of d. You can also see that the maximum of the small-signal gain $Gain$ is achieved at a certain length of the modulator due to the features of the profile of the charge carrier concentration n, which arises along the modulator when pumped. Therefore, the general pattern of the influence of the active region thickness manifests itself in the following: the thicker is the active region, the lower is the current density at the fixed value of the pumping current (250 mA), i.e., the lower is the concentration of the carriers in the active region, which is responsible for the gain. Designs with the lower thickness of the active region provide for higher current density and, accordingly, higher values ER and $Gain$. For example, if Γ-factor is 5 %, then at the width of the active element 5 μm the condition „$ER > 10\,000$ and $Gain > 5$ dB“ will be met only at the thickness of the active region with $d < 35$ nm and modulator length of $L > 2200\,\mu$m. Let us note briefly that the thickness of the active region is related strongly to the optical confinement factor of the mode in the active region (Γ-factor), which may not take high values at low values of the thickness of the active region. Simultaneously with this the advantage of the modulator design with the active region on the basis of the bulk layer consists in the fact that when it is used, low value of polarization dependence of gain is provided due to the ability to achieve a very high Γ-factor in the active region [11].

As it was shown above, the parameters of the crystal that affect the current density at the fixed pumping current significantly affect ER and $Gain$. Since the density of the pumping current of the modulator increases as the volume of the active region V decreases, the narrower is the active element, the higher is the current density at the same pumping current (250 mA). Therefore, it is important to estimate the influence provided at the modulator characteristics by the reduction in the width of the active element. Figures 3 and 4 show the ER and $Gain$ distribution charts obtained for the active element width reduced down to 1.5 μm.

Since in the case of $w = 1.5\,\mu$m the current density is higher compared to $w = 5\,\mu$m, then, accordingly, on charts ER and $Gain$ higher values are achieved in the wider ranges of parameters L and d. For example, $ER > 10\,000$ may be obtained for the designs having at the same time all the permissible values of thicknesses of the active region (20–80 nm) at crystal lengths of $> 2500\,\mu$m, which was not achieved for the width of the active region of 5 μm, and the condition of $Gain > 5$ dB is met for the entire chart (Figure 4). However, when the design is selected with the narrow aperture of radiation, it is necessary to consider the significantly higher requirements to the precision of the alignment system when the radiation enters the optic fibre, failure to meet which may result in lower efficiency of the system that includes such modulator, due to the potential optical losses. Another extreme are the designs with the broad radiating aperture. Thus, for example, the broadening of the aperture of the active element to 8 μm at the fixed Γ-factor 5 % results in the fact that the condition „$ER > 10\,000$ and $Gain > 5$ dB“ is not met for the long resonant cavities and thick active regions. It is important to note that the expansion of the active element also may be implemented due to current spreading in the lateral direction. This means that the current spreading must be prevented, which may be achieved by using the design of the active element with the dramatic current restriction.

If the maximum Γ-factor is provided at the minimum thickness of the active region, the maximum gain may be achieved, which is explained by the ability to accumulate higher concentration of charge carriers in the active region and, as a result, higher material gain is achieved. For

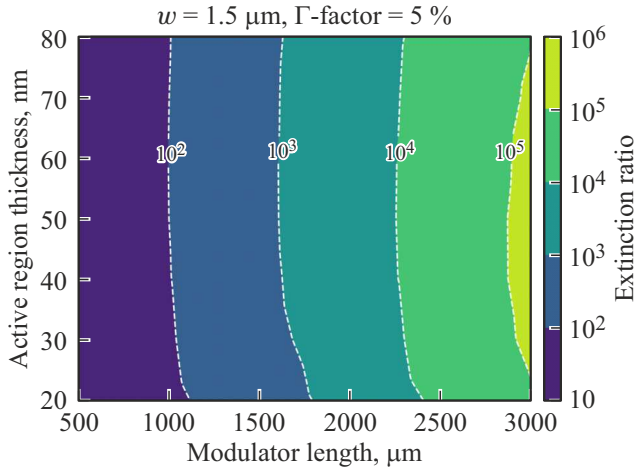


Figure 3. Extinction ratio depending on parameters d and L at $w = 1.5\,\mu$m, $\Gamma = 5\,\%$.

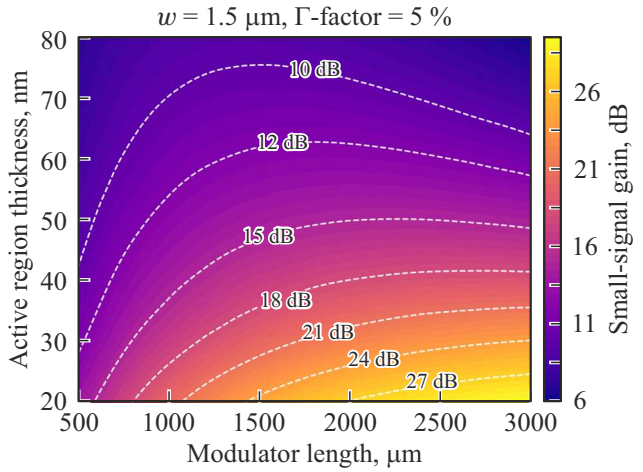


Figure 4. Small-signal gain depending on parameters d and L at $w = 1.5\,\mu$m, $\Gamma = 5\,\%$.

example, if Γ-factor is 7.5 %, then at the width of the active element of $5\,\mu$m the condition „$ER > 10\,000$ and $Gain > 5$ dB“ will be met at the thickness of the active region of < 40 nm and the modulator length from 2000 to $2500\,\mu$m, and the decrease in the thickness of the active region down to 30 nm makes it possible to expand the permissible range of the modulator lengths due to the use of longer crystals (up to $3000\,\mu$m). You can see that the increase of the Γ-factor may significantly rectify this situation. Thus, at the width of the active element of $8\,\mu$m and increase of the Γ-factor from 5 to 7.5 % the condition „$ER > 10\,000$ and $Gain > 5$ dB“ may already be met, however, for this the thickness of the active region must be decreased down to 20 nm, and the permissible lengths are from 2000 to $3000\,\mu$m. Further increase of Γ-factor to 15 % makes it possible to move the structures to the area of thicker active regions and to meet the condition „$ER > 10\,000$ and $Gain > 5$ dB“ at the thickness of the active region of < 80 nm and modulator length from 1000 to $1500\,\mu$m. Besides, the decrease in the thickness of the active region makes it possible to move the boundary of the permissible maximum length of the modulator to the area of longer crystal lengths: at the thickness of the active region of < 70 nm the permissible lengths of the modulator are in the range from 1000 to $2000\,\mu$m, at the thickness of the active region of < 60 nm — from 1000 to $2500\,\mu$m, at the thickness of the active region of < 50 nm — from 1000 to $3000\,\mu$m. At the width of the active element of $8\,\mu$m and thickness of the active region from 60 to 80 nm the condition „$ER > 10\,000$ and $Gain > 5$ dB“ is met only at the modulator length of $1000\,\mu$m, which makes it possible to use the design of the active element with a less dramatic current restriction at the nominal width of the active element of $5\,\mu$m, permitting current spread to $8\,\mu$m.

The optimal Γ-factor from the technology point of view may be the value of 12 %. In the group of dependences

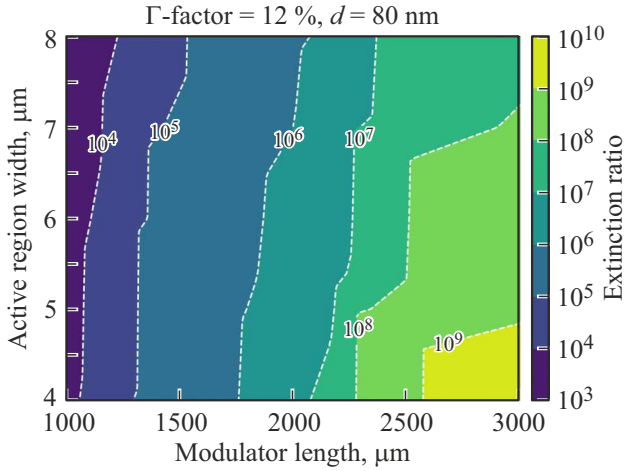


Figure 5. Extinction ratio depending on parameters w and L at $d = 80$ nm, $\Gamma = 12\,\%$.

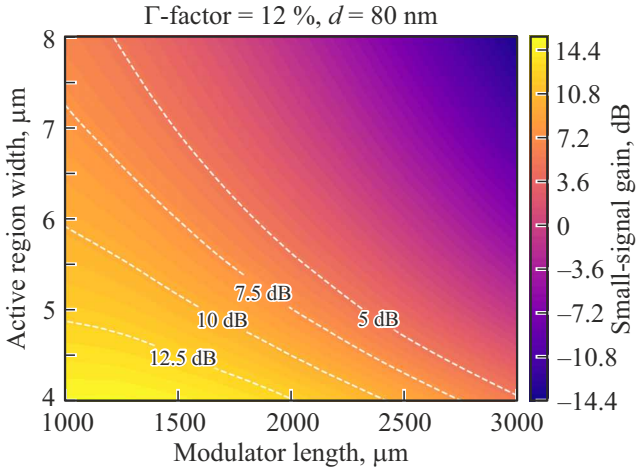


Figure 6. Small-signal gain depending on parameters w and L at $d = 80$ nm, $\Gamma = 12\,\%$.

of the extinction ratio (Figure 5) and small-signal gain (Figure 6) on the modulator length and the active element width at the fixed values of the optical confinement factor in the active region and thickness of the active region (Γ-factor = 12 %, $d = 80$ nm) you can see that at the modulator length of 1200 μm the condition „$ER > 10\,000$ and $Gain > 5$ dB“ will be met for any width of the active element of $< 8\,\mu$m, which allows, for example, using the design of the active element with a less dramatic current restriction at the nominal width of the active element of 5 μm. At the same time it should be noted that in this case the optimum is achieved at the short length of the modulator, which must provide for a lower noise factor.

4. Conclusion

It is shown that the described optimization unidimensional calculations make it possible to select the designs of the heterostructures for the development of the semiconductor optical gate with the required characteristics. The conducted calculations have shown that the permissible parameters of the crystals of optical modulators may stay within rather wide ranges of values, which allows implementing such instruments on the basis of the available designs of heterostructures and with the lower requirements to the precision of the crystal structure manufacturing. In the general case the increase in the current density in the on state due to the decrease in the width and length of the active element or decrease of the thickness of the active region does not always improve the modulator characteristics, therefore, numerical optimization calculations are necessary to select the optimal designs. To determine the optimal values of the active region thickness and the optical confinement factor related to each other, it is necessary to conduct additional studies of the waveguide structures.

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Conflict of interest

The authors state that they have no conflict of interest.

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