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Operation of arsenide diode lasers at elevated temperatures

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Some design modification and optimisation of the GaAs/(AlGa)As separate-confinement-heterostructure (SCH) as well as the graded-index separate-confinement-heterostructure (GRIN-SCH) semiconductor lasers are discussed to reduce their threshold concentrations at elevated temperatures. A detailed optical model of arsenide lasers is used to compare an impact of some structural details on lasing thresholds at various temperatures. In the analysis, both optical gain and losses are modelled rigorously. It has been demonstrated that operation of arsenide lasers considered is not changing dramatically at elevated temperatures not exceeding 400 K.

1. Introduction

Compared to classical double-heterostructure (DH) lasers, semiconductor lasers with single quantum well (SQW) active regions exhibit much lower lasing thresholds, mostly because of the quantum-size effect [1], *i.e.*, lower quantized state densities and higher carrier densities in two-dimensional QW structures. Efficiency η_{inj} of collecting injected carriers as well as optical confinement factor Γ_{QW} both in quantum-well active regions, are additionally improved in the separate-confinement-heterostructure (SCH) lasers, where confinement mechanisms for carriers and for an optical field may be optimised separately. Even better results are expected in graded-index separate-confinement-heterostructure (GRIN-SCH) lasers. An impact of some modifications of GRIN-SCH lasers on their threshold, confinement factor and effective index of refraction has been reported. The main goal of this work is to discuss the influence of lasing operation at elevated temperatures on these quantities using the approach put forward in [2].

2. Model

The optical gain model has been based on Fermi's Golden Rule and the envelope/Bloch function formalism for the electron and hole wave functions. Gain curves determined for GaAs/$Al_{0.3}Ga_{0.7}As$ SQWs with the model reported in [3] are presented in Fig. 1. There are two kinds of absorption processes taken into account in our model: the band-to-band absorption (within all semiconductor layers, except active ones) determined on the basis of the experimental results obtained by

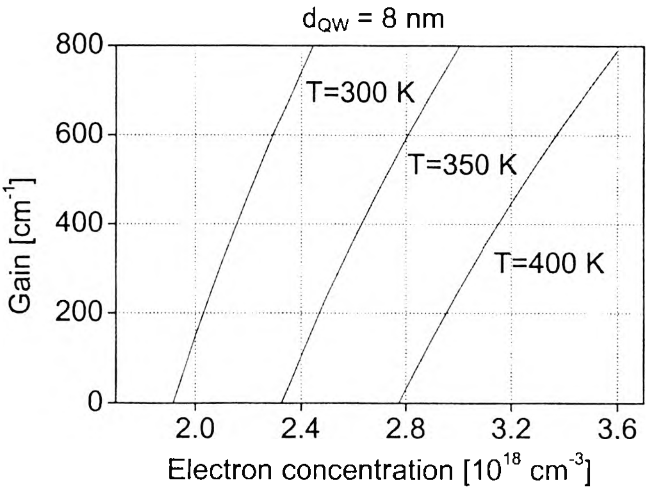

Fig. 1. Calculated profiles of the maximal optical gain for 8-nm single quantum well versus electron concentrations within the GaAl/$Al_{0.3}Ga_{0.7}As$ SQW active layers at various temperatures.

ADACHI and BLAKEMORE [4], [5] and the free carrier absorption (within all semiconductor layers) calculated with the aid of data given in [6]. The degree of dopant activation has been determined using the approach explained in [7]. In the optical model, diffraction losses, *i.e.*, unfavourable penetration of passive areas by the optical field, are introduced by the model itself. Other possible absorption processes and all scattering losses are not taken into account; they may, however, be considerably reduced using a precise technology. Also end losses, being the result of emission an of output beam, are omitted. The last loss mechanism is, however, practically the same for all TE radiation modes. Therefore, it may be considered only as an additional factor increasing proportionally all lasing thresholds. Refractive index values have been derived from the results given in [8]. The relation between the wavelength of emitted beam and the temperature has been found on the basis of experimental results obtained by WRÓBEL [9]. The model used in these calculations is explained in detail in [2]. First results of this approach have been reported in [10].

3. Results

3.1. The SCH lasers

The typical SCH-SQW structure under consideration (Fig. 2**a**) is composed of the SQW GaAs active layer placed in the very middle of the uniform $Al_{xw}Ga_{1-xw}As$ waveguide surrounded by two $Al_{xc}Ga_{1-xc}As$ claddings, where $xc > xw$. For such a laser, some results determined using the model are shown in Fig. 2, which enables discussion of an influence of the waveguide width d_w on laser threshold properties. To obtain high Γ_{QW} values, the waveguide should not be too thin since then the optical field will penetrate both the n- and p-type claddings to an unaccepted extent.

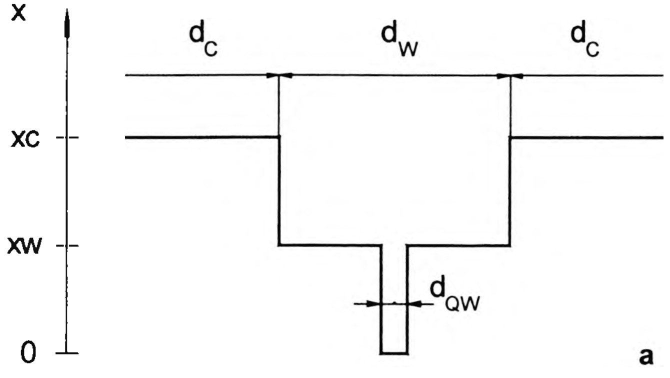

Fig. 2a

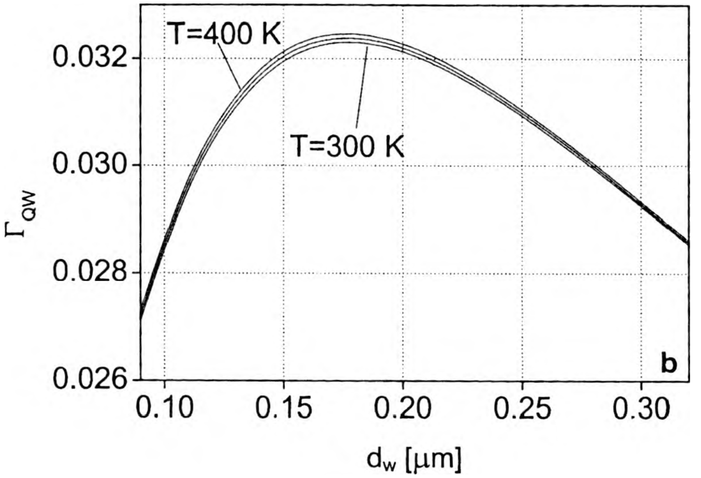

Fig. 2b

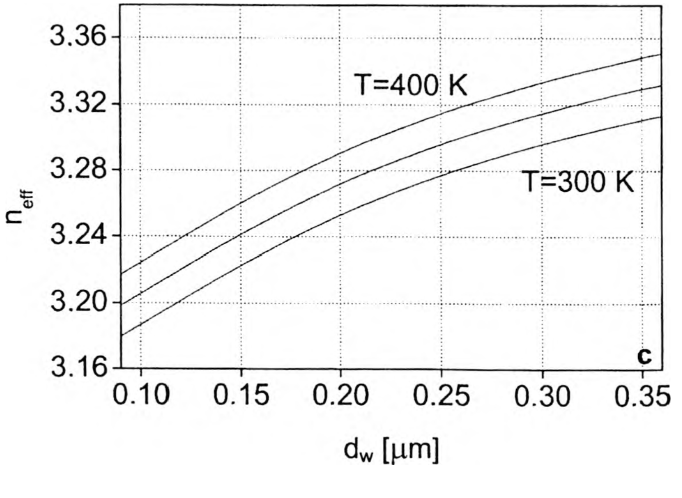

Fig. 2c

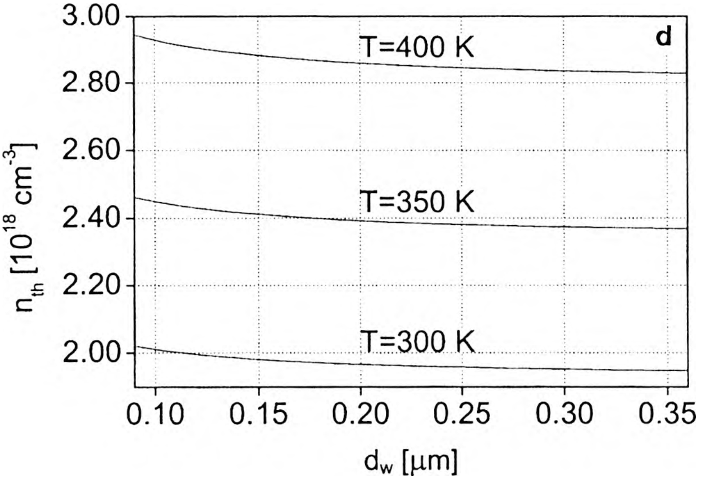

Fig. 2. SCH-SQW structure under consideration: **a** — variation of the AlAs mole fraction x (basic design parameters are also shown), **b** — the confinement factor Γ_{QW} in the typical SCH laser (the GaAs SQW active layer (of a given thickness d_{QW}) inside the $Al_{0.3}Ga_{0.7}As$ waveguide), **c** — the effective index of reraction η_{eff}, and **d** — the threshold carrier concentrations n_{th} versus the waveguide width d_w at different temperatures: 300, 350 and 400 K.

On the other hand, however, it should not be too thick either, since then the smaller part of the field will interact with carriers inside an active region, so the Γ_{QW} confinement factor will be reduced (Fig. 2**b**). Therefore, there exists an optimal waveguide width equal in this case to about $d_w = 160$ nm, regardless of the temperature.

The value of confinement factor is slightly increasing with an increase in temperature. It is mostly a result of two opposite processes: on the one hand, the refraction indices of semiconductor layers are increasing with temperature (*cf.* Fig. 2**c**), but at the same time increasing temperature causes a shift of the wavelength in the IR direction which is followed by the lowering of refraction indices. As one can see, the first process is faster. A threshold concentration (Fig. 2**d**) also increases with temperature, but this effect is mostly caused by decreasing optical gain. The band-to-band absorption is increasing with the temperature as well. On the other hand, similarly to refraction index, a shift of wavelength causes a decrease in band -to-band absorption. As a result we obtain a bit lower absorption at higher temperatures.

An impact of the width d_c of cladding layers on lasing threshold has also been examined for different temperatures. It has been found that, regardless of the temperature, both claddings should be at least 0.7 – 0.8 μm wide, yet, additionaly, to make the penetration of lossy regions by laser radiation difficult claddings should be a little wider at higher temperatures. Their further increase does not practically improve the confinement of an optical field. From an electrical point of view, on the other hand, relatively high-resistive cladding layers should be as narrow as possible, so the above value may be regarded as a lower limit of their widths.

3.2. The GRIN-SCH lasers

Two modified versions of the GRIN-SCH-SQW structure under consideration are proposed in Fig. 3. In the first design (Fig. 3**a**), uniform $Al_{0.3}Ga_{0.7}As$ layers of thickness d_U are placed on both sides of the SQW active layer followed by graded (AlGa)As layers of thickness d_G. In this subsection, an influence of both the

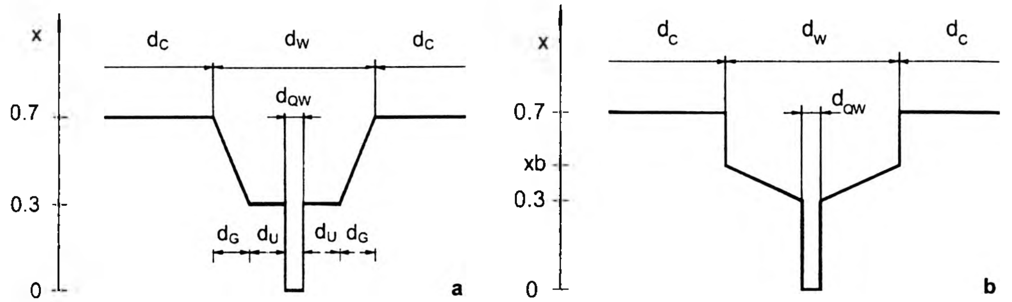

Fig. 3. Variation of the AlAs mole fraction x in the modified GRIN-SCH-SQW structure under consideration. The first device (**a**) is reduced to the standard GRIN-SCH-SQW structure and to the SCH-SQW structure for $d_U = 0$ and $d_G = 0$, respectively. Various forms (from linear to parabolic) of a change in AlAs content within the graded layer are considered. The second design (**b**) becomes the standard GRIN-SCH-SQW structure for $xb = xc = 0.7$, whereas for $xb = 0.3$ it is reduced to the SCH-SQW structure.

thickness d_U of uniform parts of the waveguide and the thickness d_G of its graded parts as well as temperature of all layers on lasing thresholds of the modified GRIN-SCH-SQW devices is examined. Additionally, various forms of a change Δx of an AlAs in graded layers

$$\Delta x \propto (x - x_G)^k \tag{1}$$

are discussed. In Eqation (1), x_G stands for the co-ordinate of a starting point of the graded layer and the exponent k may be changed from 1 (linear grading) to 2 (parabolic grading).

Figure 4 illustrates an impact of the d_U thickness on some parameters of the modified GRIN-SCH-SQW laser with $d_c = 2$ μm, $d_{QW} = 8$ nm, and $d_w = 0.248$ μm. Edge points of these plots correspond to the standard GRIN-SCH-SQW structure (for $d_U = 120$ nm). As one can see, the extremum of confinement factor (Fig. 4**a**) for different waveguide profiles is increasing with a decrease in k (*cf.* Eq. (1)). Structures with $d_U \approx 0.07$ μm exhibit the highest Γ_{QW} factors at all three different temperatures. The factors are increased by as much as 13% (*i.e.*, from 0.0282 to 0.0320) with respect to the standard GRIN-SCH-SQW structure ($d_U = 0$) with a linear ($k = 1$) profile of the AlAs mole fraction in the graded layers. Some

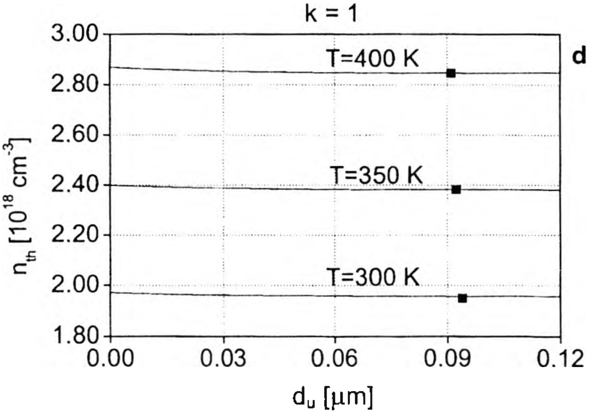

Fig. 4. Impact of the thickness d_U of a uniform part of the waveguide (*cf.* Fig. 3**a**) of the first modified GRIN-SCH-SQW laser ($d_C = 2$ μm, $d_{QW} = 8$ nm and $d_W = 0.248$ μm) on: **a** – the confinement factor Γ_{QW} within the SQW active layer at 350 K, **b** – effective index of refraction at three different temperatures 300, 350 and 400 K, and $k = 1$, **c** – the threshold carrier concentration at 350 K; successive curves are plotted for $k = 1$, 4/3, 5/3 and 2, **d** – the threshold carrier concentration at 300, 350 and 500 K, and $k = 1$ (squares correspnd to minimal threshold).

additional conclusions concerning recommended grading may be deduced from the figure. First of all, parabolic grading ($k = 2$) is found to ensure better field confinement within the SQW active layer than the linear one in the case of the standard structure ($d_U = 0$). In the modified structure, however, linear grading enables obtaining slightly better results. To achieve maximal Γ_{QW} values, thicker d_U layers should be applied for decreasing k exponents (*cf.* Eq. (1)) in graded layers. Also slightly better results are achieved at elevated temperatures.

An effective index of refraction is also increasing with an increase in d_U (Fig. 4**b**) because of the better field confinement within the waveguide of higher refractive index than that of claddings. Additionally, the index also increases with temperature due to an increase in refractive indices of layers.

Plots of threshold carrier concentration versus d_U for 350 K are shown in Fig. 4**c**. Parabolic grading turns out to reduce lasing threshold in the standard GRIN-SCH-SQW laser ($d_U = 0$) with respect to a linear one. Further improvement may be achieved using the modified version of this device with $d_U \approx 0.09$ μm.

Plots of threshold carrier concentration for $k \approx 1$ versus d_U for the temperatures: 300, 350 and 400 K are shown in Fig. 4**d**. The lowest temperature ensures the lowest threshold concentration which increases rapidly with an increase in temperature. The values of du corresponding to the minimum in the carrier concentration (indicated by squares) slowly decrease as the temperature grows. It is interesting to note that the optimal d_U value, ensuring the lowest lasing threshold, is found to be slightly larger than the one which gives the highest Γ_{QW} value (*cf.* Fig. 4a). This effect is caused by the better field confinement within the waveguide. The simple SCH-SQW structure ($d_U = 120$ nm) surprisingly exhibits

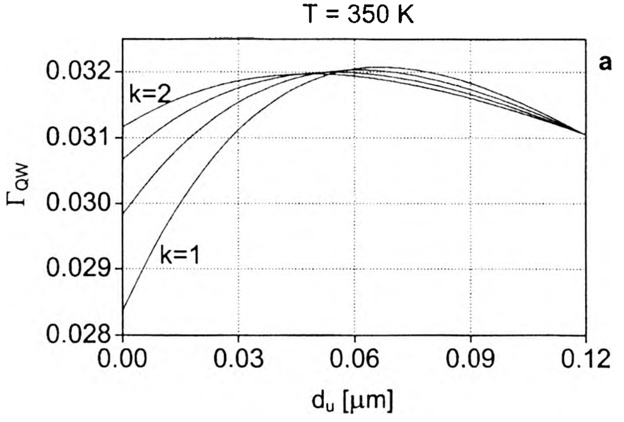

Fig. 4**a**

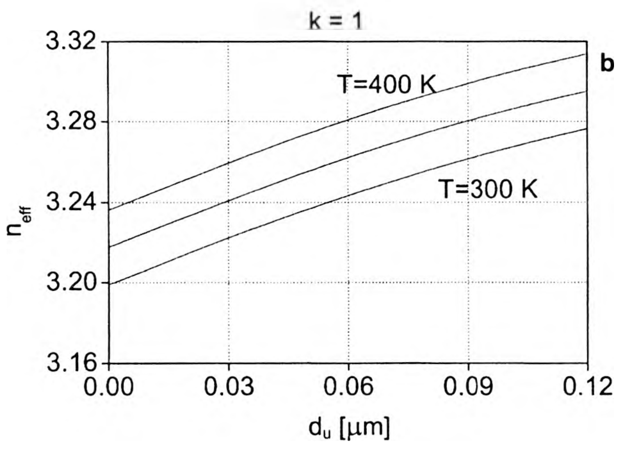

Fig. 4**b**

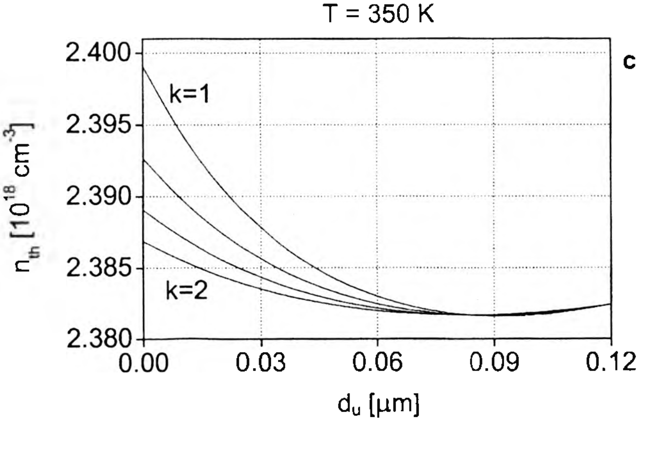

Fig. 4**c**

lower threshold than the standard ($d_U = 0$) GRIN-SCH-SQW structure at various temperatures. It should, however, be remembered that the GRIN structure produces additionally the electric field increasing an efficiency of carriers collecting within a thin SQW active layer [11]. The above effect is not included in our model. Therefore, the GRIN structure may considerably improve lasing performance of the SCH devices.

3.3. Comparison between various SCH structures

Let us first compare the SCH-SQW structure with the standard ($d_U = 0$) GRIN -SCH-SQW structures equipped with linear or parabolic gradings. The results for three temperatures are illustrated in Fig. 5. For $d_W = 0.248$ μm, values given in Fig. 5**a** are identical with those obtained from Fig. 2**b** for $d_U = 0$. For each

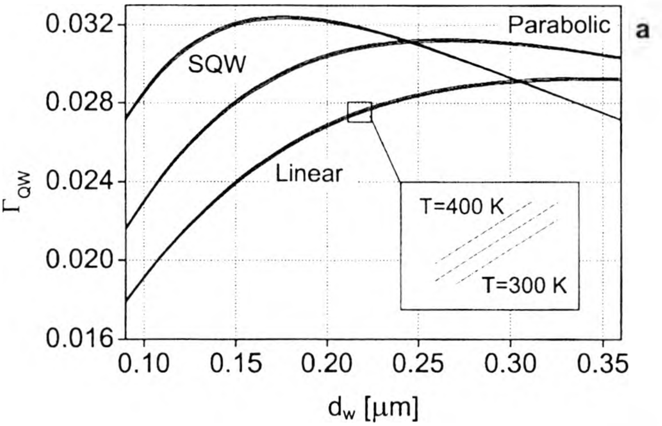

Fig. 5**a**

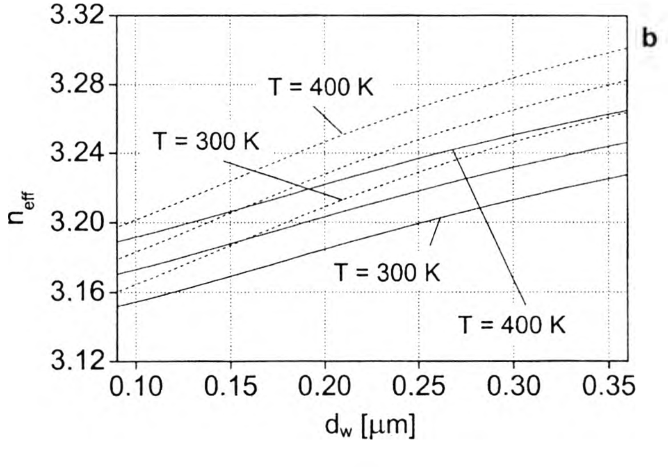

Fig. 5. Comparison between the SCH-SQW structure and the standard GRIN-SCH-SQW structure ($d_U = 0$) with both the linear and parabolic grading presenting an impact of the waveguide thickness d_W and temperature on: **a** — the Γ_{QW} confinement factor, **b** — the effective index of refraction, both for $d_{QW} =$ 8 nm (dashed lines correspond to parabolic grading, solid ones — to linear grading).

structure, the bottom lines correspond to temperature equal to 300 K, whereas the upper one – to 400 K. It is evident that for relatively narrow waveguides, the simple SCH-SQW structure may ensure better field confinements than the structure with graded interfaces. However, taking additionally into account the collecting of carriers within the SQW active layer, which is definitely more efficient in GRIN structures [11], thresholds of these more advanced devices are expected to be lower than those of the above simple SCH devices. Nevertheless, it should be noted that optimal d_W values are in the standard GRIN structures (for which they are equal to about 0.27 μm and 0.35 μm for parabolic and linear gradings, respectively) considerably larger than those for the SCH structure. It is also worthwhile to note that the parabolic grading usually ensures better confinement than the linear one and that an increase in temperature slightly improves energy exchange between carriers and an optical field (described by the Γ_{QW} factor). Figure 5**b** illustrates an impact of d_W and temperature on effective index of refraction in two waveguide profiles. Dashed lines correspond to the parabolic grading, and solid lines to the linear one. The bottom pair of lines corresponds to temperature equal to 300 K, whereas the upper one to 400 K. The parabolic grading ensures higher values of effective refractive index, which is caused in that case by a higher value of refractive index in the active region neighbourhood. The effective index of refraction is also increasing with an increase in temperature.

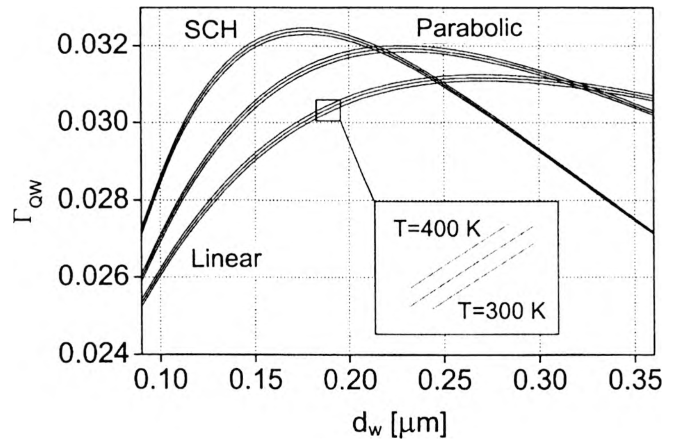

Fig. 6. Comparison between the SCH-SQW structure and the modified GRIN-SCH-SQW structure ($d_U = 0.03$ μm) with both the linear and parabolic grading presenting an impact of the waveguide thickness d_W and temperature on the Γ_{QW} confinement factor.

In Figure 6, analogous comparison between the SCH-SQW structure and the first modified (assuming $d_U = 0.03$ μm) GRIN-SCH-SQW structure (Fig. 3**a**) with both linear and parabolic grading at three temperatures is shown in Fig. 6. The plot presents dependences of the waveguide thickness d_W on the field confinement factor Γ_{QW} within the SQW active layer (Fig. 6). Curves plotted for the SCH-SQW structure are identical with those shown in Fig. 5**a**. As one can see, an additional degree of freedom (the thickness d_U of a uniform part of the waveguide) enables better than previously field confinement within the SQW active layer. Therefore, this design seems to be more promising than the standard one as a low-threshold laser device operating at room temperature and also at elevated temperatures.

4. Conclusions

The operation of various GaAs/(AlGa)As separate-confinement-heterostructure lasers, *i.e*,. simple SCH lasers as well as standard and modified GRIN-SCH lasers, has been examined at three different temperatures using a detailed optical modelling to discuss an impact of design parameters on their RT low-threshold operation. For all three versions of the SCH lasers, recommended design parameters have been determined. Surprisingly, from an optical point of view, performance of a relatively simple SCH structure has been found to be at least comparable with that of much more complex GRIN structures. This conclusion is in agreement with observed properties of both the above SCH structures [12]. The modified GRIN-SCH design (Fig. 3**a**) with additional degree of freedom of its construction enables a more advanced modelling of an optical-field profile within the laser structure. The changes in confinement factor of the structures examined have slightly increased with an increase in temperature; this has been caused by increasing the refractive indices of layers. Decreasing optical gain and increasing band-to-band absorption have produced a significant increase in the threshold concentration with temperature. The impact of increasing temperature on operation of structures under consideration has been found to be less severe than it could be expected.

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