Concept of the InGaAs Plasmonic Waveguide for Quantum Cascade Laser Applications

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Abstract. *Quantum cascade lasers are sophisticated devices mostly based on InGaAs/AlInAs/InP heterostructures to improve thermal performance. Their structure consists of a core containing hundreds or even thousands of thin layers, covered on both sides with thick cladding waveguides. Such a laser design creates enormous stresses in the core and can cause degradation of the entire device. An alternative to the thick InP claddings are thin, highly doped InGaAs layers used as plasmonic waveguides. This solution allows to achieve a mode confinement above 50 % even at only 150 nm of the waveguide layer, which is extremely difficult in the case of standard designs. The article presents theoretical simulations concerning the influence of the InGaAs plasmonic layer on the mode confinement.*

Keywords

InGaAs, Low-Pressure Metalorganic Vapour-Phase Epitaxy, plasmonic waveguide, QCL.

1. Introduction

Quantum Cascade Lasers (QCLs) are unipolar devices based on intersubband transitions [1]. The design of the laser and the thickness of individual layers have a key impact on the emitted wavelength [2]. The core of QCL contains hundreds or even thousands of thin layers with a thickness of the order $0.5 - 10$ nm. Because of the sophisticated nature of QCL, it is important to deposit layers of strictly defined composition and thickness [3].

The critical elements in QCL construction are claddings with certain free carriers concentration profiles, which ensure the distribution of the fundamental mode in the laser core. The thickness, as well as doping profile, affect not only the confinement of the mode but also the free carrier absorption (losses) and threshold gain. Usually, QCL contains core and suitably doped thick claddings e.g. based on indium phosphide. The deposition of thick layers significantly extends the time of epitaxial growth, which affects the quality of interfaces due to the long annealing process and consequently increases costs. In addition, claddings reduce heat dissipation from the core of the laser what leads to heating of the structure [4].

An alternative idea for standard thick claddings is to use thin, highly doped plasmonic InGaAs layers [5]. Thanks to this it is possible to reduce the overall thickness of the laser structure and thus decrease both duration of the epitaxy and process costs. The use of the substrate as the bottom waveguide and the thin InGaAs plasmonic layer as the top one allows the total thickness of the epilayers to be reduced by up to half. Application of InGaAs ternary alloys allows achieving a high doping concentration without decreasing a crystalline quality as well as a formation of ohmic contact, without the necessity of thermal annealing. In addition, the serial resistance of the whole device reduces, which results in lower working voltage.

Epitaxial growth of InGaAs plasmonic layers is a huge technological challenge because it requires a very high doping level, exceeding $1 \cdot 10^{19}$ cm^{-3}, and both a high crystalline together with perfect optical quality. In the article, the influence of plasmonic InGaAs waveguide design on the optical losses and mode confinement, based mainly on theoretical considerations, is presented [6].

2. Results and Discussion

In theoretical model, the attention was focused only on the highly doped InGaAs layer working as the top waveguide. The simulations were carried out for the wavelength of 8 μm - due to the correlation presented in the literature [5] between the doping level for InGaAs lattice-matched to InP and complex refractive index. The values of parameters, such as the refractive index n, extinction coefficient k and the corresponding doping level n_0, are included in Tab. 1.

Tab. 1: The values of the doping level, refractive index and extinction coefficient of InGaAs lattice-matched to InP determined for 8 μm.

n_0 Doping level $\cdot 10^{19}$ cm^{-3}	n Refractive index	k Extinction coefficient
1.2	0.85717	0.348878
1.3	0.50000	0.628690
1.3	0.43485	0.748880
1.4	0.32769	0.976540
1.5	0.22439	1.218800

The optimal level of doping concentration and the thickness of a thin plasmonic layer were investigated in order to minimize plasmonic leakage and improve the mode confinement. The modeling approach was used for the determination of the influence of design construction on mode confinement in the laser core Γ and percentage leakage of the laser mode on the plasmonic layer $\Gamma_{plasmon}$. A dedicated python based script was written using the CAMFR full-vectorial Maxwell solver [7] as the calculating tool. Based on eigenmode expansion, structures were divided into a finite number of layers where the refractive index does not change in the z-direction. The main focus was on the electrical component of the TM mode E-TM due to selection rules for intersubband transitions in quantum wells. In the case of plasmonic layers - apart from the refractive index, an extremely important parameter is the extinction coefficient k which significantly affects the distribution of the laser mode [5]. Γ parameter was determined from the integral of the square of the electrical component of the TM mode E^2-TM in the core. In a similar way was estimated the percentage leakage on the plasmonic layer $\Gamma_{plasmon}$. The simulations were carried out for different thicknesses d (50−500 nm) and doping concentration levels n_0 ($1.2 - 1.5 \cdot 10^{19}$ cm^{-3}) of the top InGaAs layer. For a better comparison of the obtained results, the value of E^2-TM has been normalized.

Figure 1 presents the change in the distribution of E^2-TM along the whole structure as a consequence of increasing the thickness of the plasmon InGaAs top layer doped at the level of $n_0 = 1.3 \cdot 10^{19}$ cm^{-3}. In the case of the narrow 100 nm thick InGaAs layer

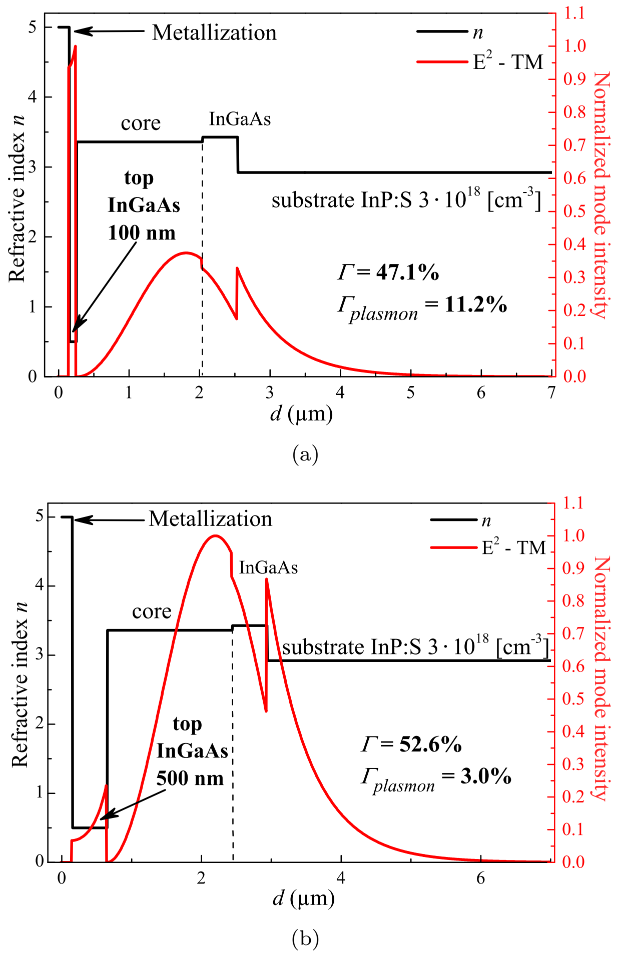

Fig. 1: Distribution of the refractive index n (black line) and the square of electrical component of the TM mode E^2-TM (red line) in the QCL structure with a) 100 nm and b) 500 nm InGaAs plasmonic layer for $n_0 = 1.3 \cdot 10^{19}$ cm^{-3}.

(Fig. 1(a)), the highest intensity of the mode is observed in the plasmonic area what corresponds to significant losses in mode confinement Γ and a large plasmonic leakage $\Gamma_{plasmon}$ (11.2 %). Increasing the width of the InGaAs layer to 500 nm enhances the mode confinement and significantly reduces the value of $\Gamma_{plasmon}$ to 3 % (Fig. 1(b)). The intensity of the laser mode is almost five times higher in the core region than in the plasmonic area which is evident in the improvement of QCL parameters. Analogous simulations were carried out for another plasmonic layer thicknesses changing from 100 − 500 nm for $n_0 = 1.3 \cdot 10^{19}$ cm^{-3} and different doping concentration levels n_0 varied from $1.2 - 1.5 \cdot 10^{19}$ cm^{-3} at $d = 500$ nm. Based on the obtained results the dependences of Γ and $\Gamma_{plasmon}$ parameters on the InGaAs top layer thickness d and carrier concentration n_0 were determined and shown in Fig. 2.

On the basis of Fig. 2(a), it was found that with increasing thickness of the InGaAs plasmonic layer up to

300 nm the mode confinement increases and plasmon leakage significantly decreases, while for $d > 300$ nm a saturation of both dependences is observed. Such correlation for all levels of carrier concentration is observed. The impact of the carrier concentration modification at the constant thickness of the plasmonic layer $d = 500$ nm was also analyzed (Fig. 2(b)). As the concentration increases the mode confinement Γ is slightly reduced and at the same time, the plasmonic leakage $\Gamma_{plasmon}$ is significantly decreased. Waveguide losses due to leakage on the surface plasmons $\alpha_{plasmons}$ can be described by the formula:

$$\alpha_{plasmons} = \frac{4\pi n_m n_d^3}{k_m^3 \lambda}, \tag{1}$$

where λ is the wavelength, n_m and k_m are the real and imaginary parts of the complex refractive index of the metal (in this case they refer to n and k parameters of highly doped InGaAs layer), and n_d is the real part of the complex refractive index of the dielectric material (in our case a laser core: $n_d = 3.36$) [8].

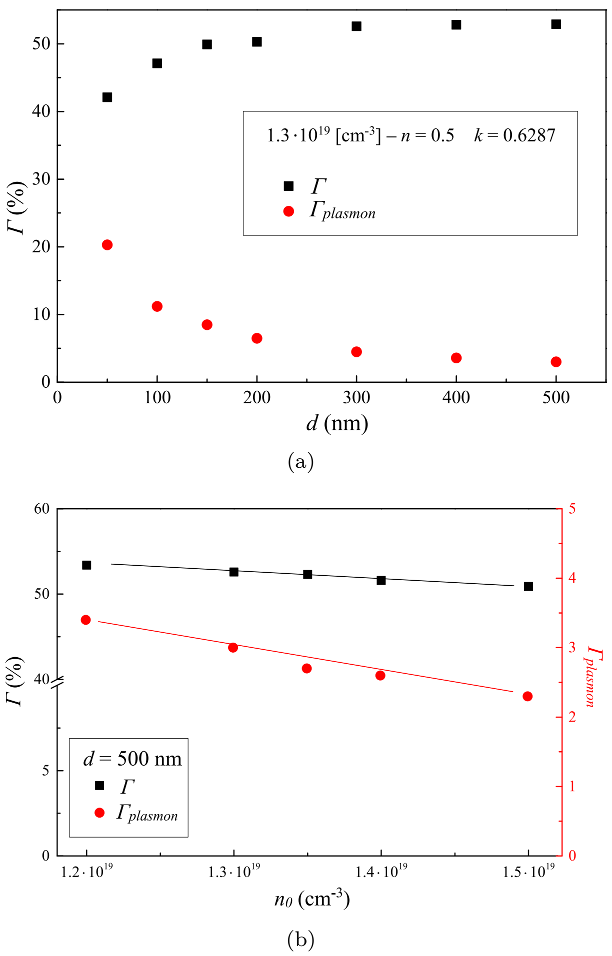

Fig. 2: The dependences of Γ and $\Gamma_{plasmon}$ as a function of: a) top InGaAs layer thickness d for $n_0 = 1.3 \cdot 10^{19}$ cm^{-3}; b) top InGaAs layer doping levels n_0 for $d = 500$ nm.

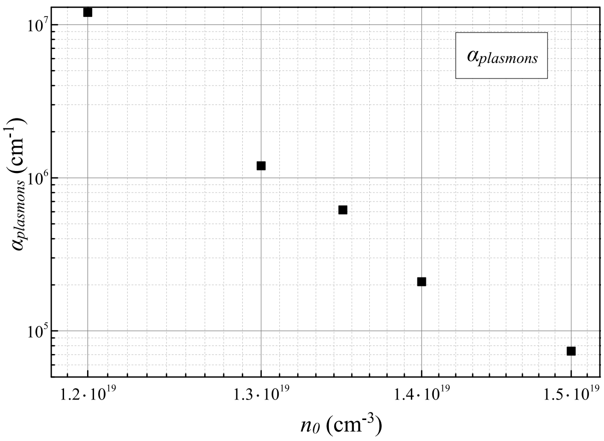

Fig. 3: Dependence of plasmonic losses at the interface $\alpha_{plasmons}$ between the highly doped InGaAs and the core on the doping level n_0.

Based on Fig. 3, it was found that on a logarithmic scale the relationship between plasmonic losses at the interface and the doping level n_0 is linear. As the doping level increases, the losses decrease, mainly due to a strong increase in the extinction coefficient with a slightly changing refractive index. The losses on this interface are very high due to the low extinction coefficient for InGaAs compared to standard metallic layers.

A very important parameter in the point of view of QCL spectral range of work is connected with absorption losses on free carriers α_{fc}. Assuming an ideal situation when all dopant atoms are ionized giving free carriers ($n_0 = N$), the α_{fc} value can be calculated using the Eq. (2):

$$\alpha_{fc} = \frac{e^2}{4\pi^2 c^3 \epsilon_0 n_{eff}} \cdot \frac{N\lambda^2}{m^* \tau}, \tag{2}$$

where e is elementary charge, c velocity of light, ϵ_0 vacuum permittivity, n_{eff} complex of refractive index, N carrier concentration, λ wavelength, m^* electron effective mass and τ carrier lifetime value taken on the basis of literature $\tau = 150$ fs [1]. Table 2 lists α_{fc} values calculated for $d = 500$ nm and different doping levels n_0. Losses on free carriers rise with increasing doping level, which confirms the theoretical predictions. Additionally, the parameter $\frac{\Gamma_{plasmon}}{\Gamma}$, which represents the percentage of plasmon leakage relative to the mode confinement, was determined for a better comparison of the obtained results.

Tab. 2: Collected parameters for a plasmonic layer with a thickness of $d = 500$ nm at different doping levels n_0.

Doping level n_0 (cm^{-3})	**Γ (%)**	**$\Gamma_{plasmon}$ (%)**	**$\frac{\Gamma_{plasmon}}{\Gamma}$ (%)**	**α_{fc} (cm^{-1})**
$1.20 \cdot 10^{19}$	53.4	3.4	6.3	3.3
$1.30 \cdot 10^{19}$	52.6	3	5.7	5.7
$1.35 \cdot 10^{19}$	**52.3**	**2.7**	**5.2**	**5.9**
$1.40 \cdot 10^{19}$	51.6	2.6	5.0	6.1
$1.50 \cdot 10^{19}$	50.9	2.3	4.5	6.4

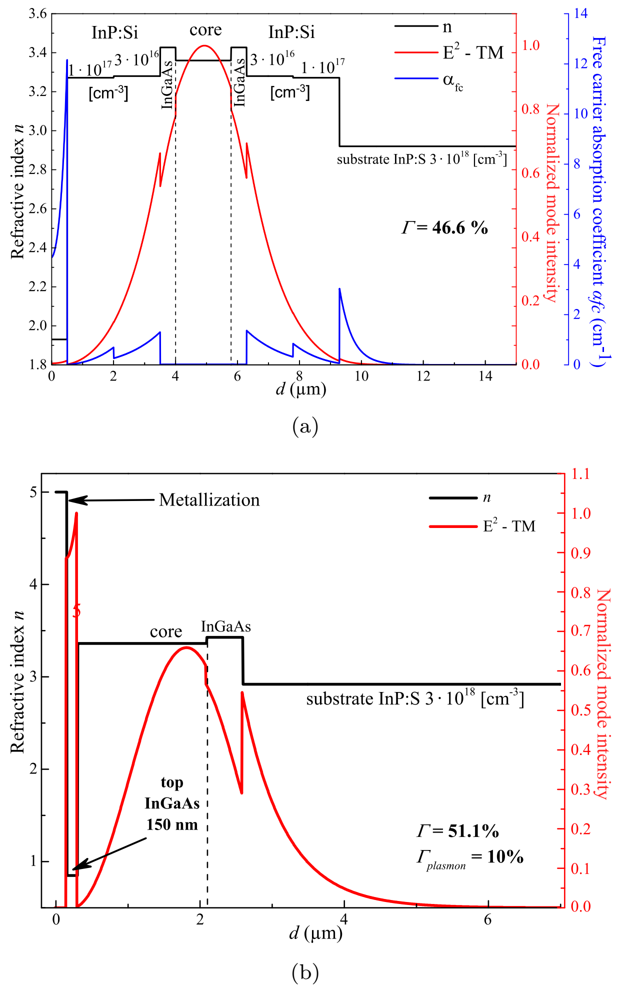

Fig. 4: Theoretical simulations of a) standard 3 µm thick InP waveguide and b) 150 nm thick top InGaAs waveguide for $n_0 = 1.2 \cdot 10^{19}$ cm^{-3}.

Based on the data presented in Tab. 1, Tab. 2 and Fig. 3, the optimal doping level $n_0 = 1.35 \cdot 10^{19}$ cm^{-3} was estimated. For this value of n_0, the mode confinement Γ is still very high, above 52 %, and the plasmonic leakage $\Gamma_{plasmon}$ slightly differs from the lowest value. Additionally, it is worth emphasizing that larger values of the extinction coefficient increase the absorption losses, therefore, for the discussed highest doping level, these losses could completely disturb the laser operation. In the case of the doping level of $1.35 \cdot 10^{19}$ cm^{-3}, the extinction coefficient k is slightly greater than the real part of the refractive index n (Tab. 1), which, however, gives visible effects in reducing plasmonic losses on the interface (Fig. 3).

To confirm the benefits of usage of the thin InGaAs plasmonic top waveguide in QCL constructions, theoretical simulations for the standard applied thick InP waveguide were conducted. In order to ensure complete data comparison, Fig. 4 presents the standard InP waveguide and one of the simulated InGaAs waveguide design.

The standard InP waveguide construction included two claddings: top and bottom consisting of two 1.5 µm steps with doping levels of $1 \cdot 10^{17}$ cm^{-3} and $3 \cdot 10^{16}$ cm^{-3}, respectively. In the case of such a design, it is very difficult to obtain a mode confinement above 50 %. In contrast for InGaAs plasmonic waveguide, most simulations indicate that this parameter is maintained at 50 % or more. It is worth emphasizing that in such a case while achieving better optical parameters the thickness of the epitaxial structure can be reduced by almost 6 µm. This significantly shortens the technological process, additionally reduces the cost, and allows to rely only on the epitaxial layers of InGaAs and AlInAs without InP.

3. Conclusions

In the article, the influence of the thickness and carrier concentration level of the InGaAs plasmonic layer on the basic parameters, such as mode confinement and the percentage of leakage on the plasmons, were presented. In order to design a plasmonic layer, particular attention should be paid to the selection of parameters d and n_0, because even a small change may cause the complete extinction of the radiation. On the basis of the presented results, it was found that while concentration level is constant, by increasing the width of the plasmonic layer the mode confinement increased and the leakage on the plasmons was significantly reduced. Based on the calculations it was found that a higher level of carrier concentration significantly reduces plasmonic leakage but also slightly reduces mode confinement. Calculations of plasmonic losses on the interface between the highly doped InGaAs and the laser core for different doping level n_0 revealed that on a logarithmic scale this relationship is linear, i.e. the higher n_0 concentration causes the lower plasmonic losses $\alpha_{plasmons}$. However, these losses are still very high due to the low extinction coefficient of InGaAs semiconductor layer in relation to metallic films. Comparing InGaAs plasmonic waveguides with a typical thick InP construction, it was found that even not optimized plasmonic layers give better mod confinement even with thin layers of 150 nm. Based on the presented results, the optimal doping level of $1.35 \cdot 10^{19}$ cm^{-3} was estimated and further scientific considerations will be conducted mainly around this level.

Presented simulation results encourage further consideration and experimental confirmation. The next stage of research will be to modify the plasmonic layer constant doping profile into a stepped and gradient one to minimize plasmonic losses at the interface.

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Author Contributions

A.L. developed theoretical considerations, conducted modelling and numerical simulations. M.B. prepared the input file format for the modelling program. All the authors A.L., M.B. and B.S. the authors contributed to the final version of the manuscript. B.S. supervised the project.

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